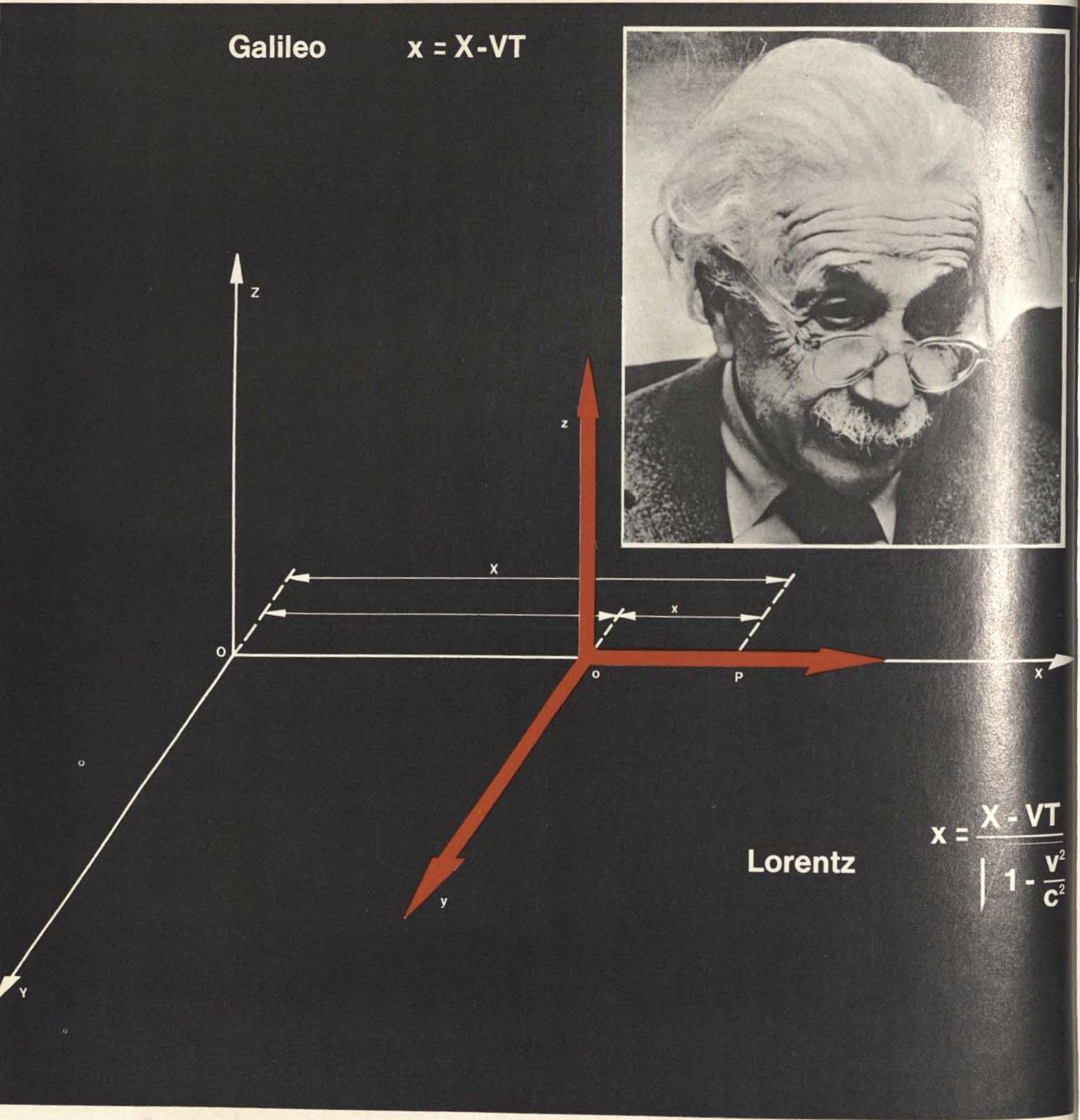
14

Illustrated World of Science Encyclopedia

Physics I: MATTER

THE WORLD OF SCIENCE



ALBERT EINSTEIN — This eminent German-Swiss-American scientist, a great figure in physics, worked out the theory of relativity.

THE WORLD OF SCIENCE

VOLUME

14

PHYSICS I

Matter

with

The Illustrated Science Dictionary

CREATIVE WORLD PUBLICATIONS, INC.
CHICAGO

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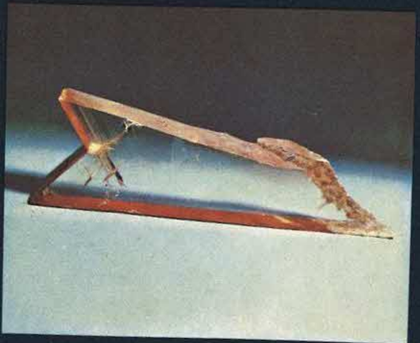

VOLUME 14

PHYSICS I

Matter

INTRODUCTION

One of the most intriguing goals of the physical scientist throughout the centuries has been to determine the basic units that make up ordinary materials. Volume 14, the first of three volumes devoted to physics, sets out to describe the physicist's present understanding of matter.

The most fundamental particles yet discovered are the elementary particles, the most familiar members of which are the electron, the proton, the neutron, and the mesons. Many of these particles were originally discovered in experiments investigating the decay of radioactive materials such as uranium, and in observations of the secondary particles produced in the atmosphere by the cosmic rays which bombard the Earth from outer space. Today, however, the elementary particles are manufactured and studied in controlled situations at the various high-energy accelerators throughout the world. The number of elementary particles discovered so far is surprisingly large—in fact, about 100. This suggests the exciting possibility that yet another level exists.

It is often convenient to consider matter as being made up of atoms and of molecules, which are small aggregates of atoms. Atoms may be thought of as particular configurations of elementary particles. At the center of an atom is a tiny cluster or nucleus composed mainly of protons and neutrons, and surrounding this nucleus is a cloud of orbiting electrons. Each element in the periodic table is distinguished by the number of protons in its nucleus, or alternately by the number of orbiting electrons. As the name implies, nuclear physics is the study of the properties of the nuclei of the various elements; some nuclei, for example, are unstable and break up, leading to radioactivity and fission. The electrons and the locations of their orbits determine the chemical properties of each element, and are intimately associated with such phenomena as magnetism and superconductivity.

This interpretation of matter in terms of atoms, molecules, and even more basic particles began with a study of matter in its more tangible forms of solids, liquids, and gases. The knowledge of the more fundamental entities unifies the physicist's picture of these three states.

Gases are made up of vast numbers of molecules or atoms in rapid random motion. The molecules are separated by large distances compared to their dimensions, so that intermolecular forces are weak. It is then easy to understand, for example, why gases are easily compressed, and how they always expand to occupy the entire volume of the enclosing vessel.

The atoms of solids, on the other hand, are tightly packed together, usually in a regular array called a crystal lattice. Strong interatomic forces allow a solid to retain its own shape, and its physical properties, such as the presence of preferred cleavage planes, can be directly related to the nature and geometric arrangement of its crystalline structure.

Liquids are intermediate between gases and solids. The intermolecular forces in a liquid are not sufficiently strong to hold the molecules in a fixed lattice position (the mobility of the molecules is easily demonstrated by the rapid diffusion of two liquids). As a consequence, a liquid has no shape of its own but conforms to the shape of the containing vessel. However, the forces are strong enough to allow a liquid to keep a constant volume.

Transitions between these three phases can likewise be directly understood in terms of the mobility of the constituent molecules and atoms. Adding heat corresponds to giving energy to individual molecules and atoms. If sufficient heat is added to a solid, the atoms can acquire enough energy to break away from their lattice positions and move around more freely (a solid melts). Similarly, a liquid can be vaporized by providing enough energy to free its constituent molecules even further.

Many exciting phenomena still require investigation, and undoubtedly many new phenomena remain to be discovered. It is not surprising, therefore, that physics remains one of the most fascinating of all the sciences.

Archibald W. Hendry, Ph.D.
Assistant Professor of Physics,
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THE ESSENCE OF PHYSICS

experiment, theory, and the science of measurable phenomena

Physics is the science of measurable quantities; specifically, it measures matter and energy. This definition is the most general possible of a science with a wide range of content, yet at the same time one of limited scope and vague boundaries.

THE SUBDIVISIONS AND LIMITS OF PHYSICS

Physics is the investigation of certain properties of any object: namely, those properties that are measurable: the weight and mass of the object, the color of its surface, and the arrangement of its atoms; how it would behave in a vacuum, or in the atmosphere; how it would react to a very high temperature, and what would happen if it were struck by a shower of cosmic rays or subjected to radiation from a nuclear reactor.

All these phenomena can be described in terms of numbers representing the development of the phenomena, or numbers representing the quantities that relate to the object itself. For example, it is possible to establish that the body under consideration weighs 27 kilograms, that its color locus is 0.321 (0.700 corresponding to green), and that if subjected to radiation in a nuclear reactor, the object will slow down neutrons bombarding it. It is also possible to establish at what points the neutrons will come to rest after being slowed down, and in what density.

These are the facts and phenomena with which physics deals, because they concern measurable quantities relating to the object under consideration. Obviously, there are many other measurable properties of the same object, but these do not all necessarily come within the range of physics. The object's capability of being imagined by the human mind, for example, is not a measurable quantity; therefore, physics is not concerned with the study of that property. This distinction is highly important in demonstrating the clear distinction between physics and philosophy. Philosophy does consider other properties of things—as, for example, whether they can be judged on the basis of aesthetic or moral principles. A description of the limits of physics is not a restriction of the potential of this science, but a clarification necessary to an objective description of the physical quantities and the physical laws with which physicists deal. Physicists seek the central ideas through which order and coherence may be brought to great areas of common experience.

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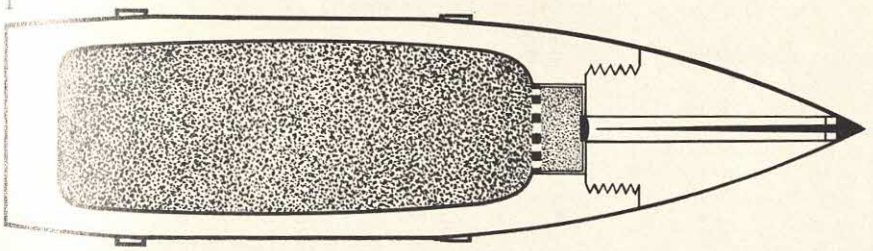
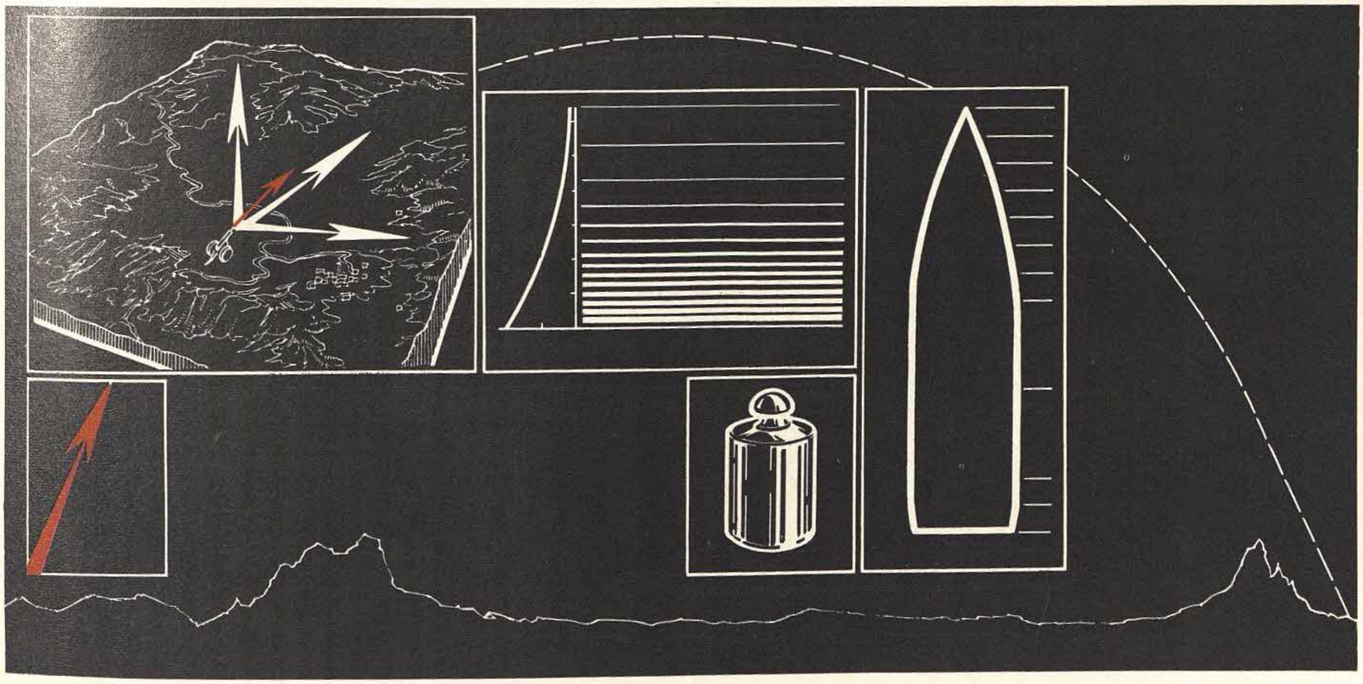


THE CALCULATION OF A BALLISTIC TRAJECTORY—To determine the trajectory of a shell, its weight, external shape, and initial velocity must be known, as well as the atmospheric conditions—or, at least, for a first approximation theory, the density of the air. The direction of firing and the range of the target must also be known. Once all these data have been established, the trajectory of the projectile can be calculated with a reasonable degree of accuracy.



PHYSICAL THEORIES

Whenever a physicist studies a phenomenon, he tries to discover mathematical laws that will allow him to describe how that phenomenon will develop under all possible conditions. If he wishes to study the trajectory of a projectile fired from a cannon at a given initial velocity in a given direction, with a given mass and subject to the resistance of the atmosphere, he will limit his study to the relevant data. This phenomenon can be explained without taking into consideration the internal structure of the projectile, the thickness of the shell case, the weight of the explosive charge, or the material of which the fuse is made.

On the other hand, the physicist must know the external shape of the projectile, because it is this shape that determines the resistance of the projectile to the air. When the motion of the projectile is studied, therefore, the projectile is considered simply as a body with a given shape and a given mass. If the initial velocity of the projectile is observed, as well as the direction of its motion and the density of the air at all altitudes through which it passes, both its range and the geometrical characteristics of its trajectory can be calculated. Ultimately, all this can be plotted to scale with extreme accuracy.

From these calculations the trajectories of projectiles of different shapes, masses, and initial velocities can be calculated. The physicist can then say that he has worked out the *theory* of motion of projectiles. The theory will consist of formulas and procedures required to predict the motion of any projectile in the atmosphere and gravitational field of the Earth.

At this point, the question arises: how valid is the theory that has been worked out? The theory is first tested by actually firing projectiles to see whether their motion is as predicted. If so, the theory is valid; if not, the theory must be rethought. There is also the possibility that the theory will prove to be only partially valid—that it may predict the motion of projectiles only up to a certain range. For example, the theory may state that all projectiles will follow the path of a parabola. In this case, the theory will prove false for calculating ranges that are large with respect to the radius of the Earth, because the path of a projectile in the Earth's field of gravity is subject to Kepler's laws, and the path actually becomes an ellipse. The path can be considered approximately a parabola only for short ranges. The longer the range, the wider the error caused by neglecting the elliptical path of a trajectory in space. The parabolic theory is, therefore, valid only for a limited category of projectiles—those fired at short range. The theory is a special case, a part of a more general theory that would explain a much larger category of phenomena. Such a parabolic theory would be called a "first approximation" theory because it comes close to the complete theory.

THE NUCLEAR REACTOR—One of the most indispensable instruments in all of modern science, the nuclear reactor is used in both experimental and theoretical nuclear physics.

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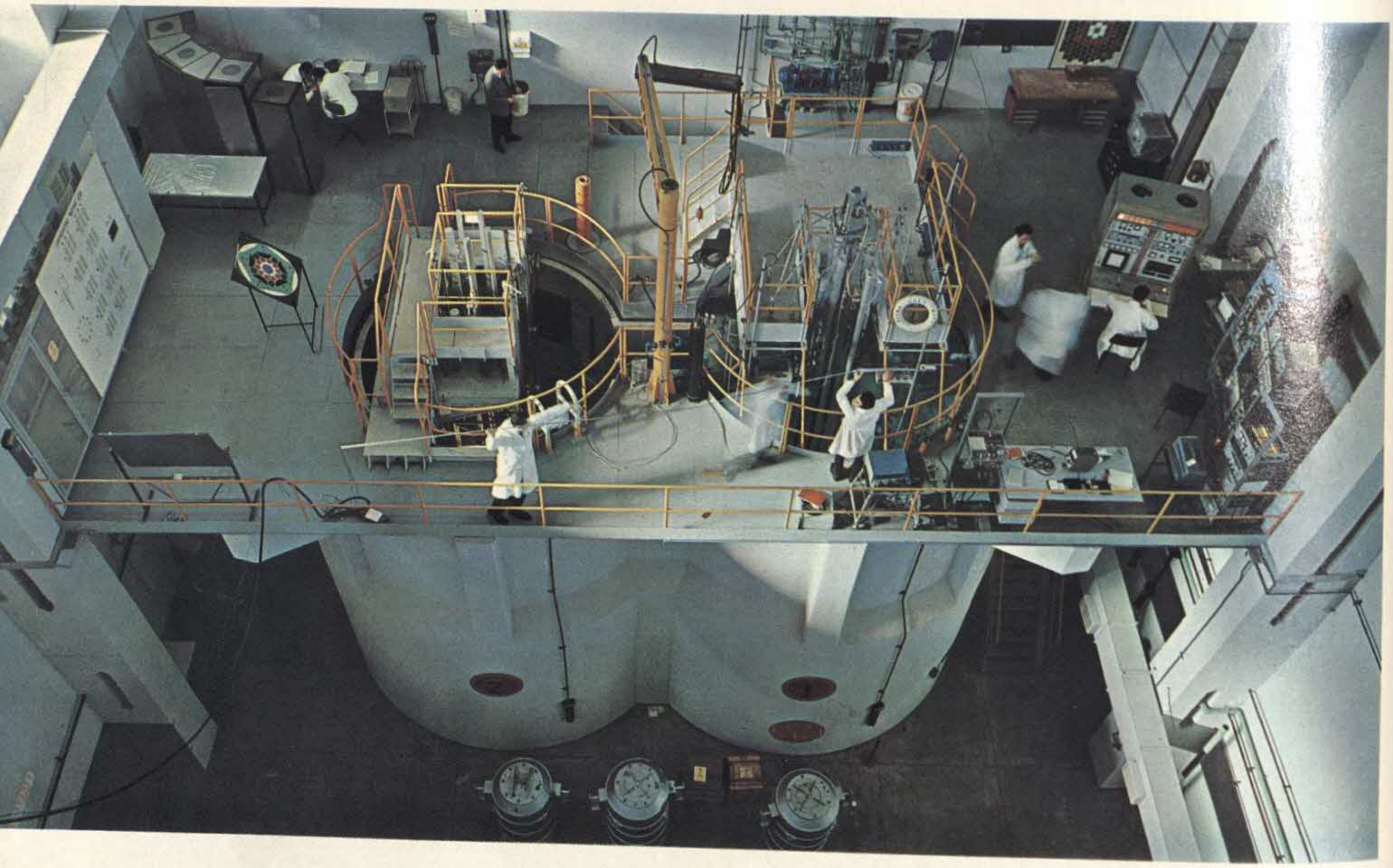

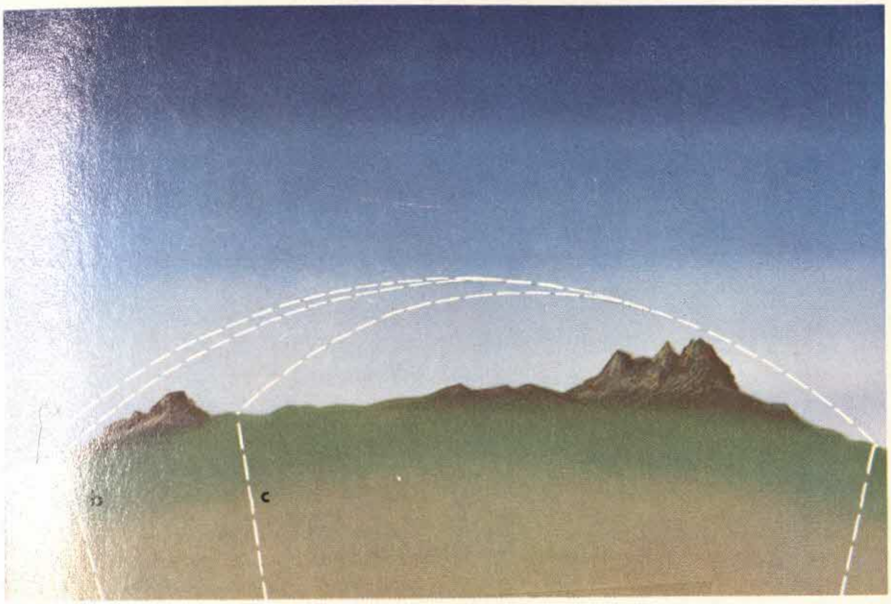

THE TRAJECTORY OF A PROJECTILE—A simple method for predicting the trajectory of a projectile through space is to imagine that its path will be a parabola, in which case the projectile should fall at point **a.** Such a theory is known as a first approximation theory. Considering that the path of a projectile around the Earth is actually an arc of an ellipse, a point of impact **b,** still closer to the actual point of impact, can be predicted. If the resistance of the atmosphere is also considered, a third point of impact **c** can be predicted. This improved approximation theory allows the determination of a point of impact very close to the actual one.

The first approximation theory and the complete theory are both examples of theories developed only *after* observing the characteristics of moving projectiles and understanding the need to express these characteristics in mathematical form in order, for example, to regulate the accuracy of artillery or missiles. Although a complete theory is obviously more satisfactory than an approximate theory, the latter may be just as useful in practice as it is simpler and therefore easier to adopt. Such theories, developed to explain given categories of phenomena are known as "interpretative" theories.

An interpretative theory may be so complete that it can lead to the discovery of new phenomena. For example, Sir Isaac Newton's theory of universal gravitation was later used to discover a new planet, Neptune, merely by calculation. The theory of universal gravitation, which interprets the behavior of falling bodies and the movements of the stars and planets, permitted the discovery of a planet unknown at the time the theory was developed. Such theories are described as "heuristic," a word developed from a Greek root and meaning "able to stimulate new discoveries and not limited to the interpretation of already known facts."

THE NEED FOR EXPERIMENTS

Experiments alone can verify the accuracy of the conclusions or predictions of a theory. A theory may lead to a number of deductions. For example, the theory of the motion of projectiles may also serve to predict the movements of artificial satellites, but only as long as no experiment contradicts the theory by its results. Only theories proved by a long series of experiments can be accepted as valid without reservations; in most cases, however, experiment and observation suggest the need for new theories or, at least, improvements in existing theories.

Toward the end of the nineteenth century, a number of experiments on the motion of bodies at speeds close to that of light exposed the inadequacy of the laws of mechanics as worked out by Galileo and Newton. Although it became clear that these laws were still valid for slower-moving bodies, the experiments showed that the laws were not universally valid. In 1905, Albert Einstein produced a new theory to explain the phenomena of bodies moving at speeds close to that of light.

Einstein's theory, known as the *special theory of relativity*, is more general than Newton's laws. It would not, however, be correct to state that the special theory of relativity produced a revolution in the laws of physics. The earlier laws were not shown to be mistaken, only incomplete; to be more exact, they were part of a more general situation explained by the special theory of relativity, and they were still adequate to explain a limited category of phenomena. Almost all progress in physics, and more generally in all of the sciences, is made through the improvement and extension of existing theories with the support and suggestions contributed by experiments. So-called scientific "revolutions" are not revolutions at all; they are periods of rapid progress.

PHYSICS AND TECHNOLOGY

New theories of physics and the experiments essential to them often require the development of special techniques. For example, a new theory often demands highly complex mathematical techniques that mathematicians themselves have not always expressed in the most convenient form. A theory may also require such a vast number of calculations that only the most up-to-date electronic computers can cope with them.

New experiments often require new and complex equipment. Yet ever since the time of Galileo, the need to perfect the techniques of mathematics and calculation and to provide newer testing equipment has led to progress not only in science, but in technology as well. Since Galileo's time, the discoveries and tools of physics have been applied to technology and industry with ever greater rapidity. Within a century of its invention the pendulum, which Galileo invented as an instrument for regulating clocks, led to the construction of virtually perfect chronometers. Similarly, high-potential electric generators were produced within decades of Michael Faraday's inventions.

Today, many discoveries and inventions are actually sought with the precise aim of putting an industrial process into operation or producing a particular instrument. Part of the research work of modern physics is done by industry.

THE USE OF MODELS | from scale model to original

A ship designer has designed a new type of hull. Scientific theory states that a ship with this type of hull will attain high speeds with relatively low power. Application of the theory is so complex, however, that it cannot be used to design and construct a full-scale prototype. Before construction can begin, the designer must know if the theory is correct. How can he test it?

The answer is simple: he can construct a scale model, one hundred times or so smaller than a full-scale one, which can be tested in a large tank of water. The main problem is to find the proper ratio between the power required for the model and that needed for the actual ship. Scientists and engineers are able to solve this problem quickly.

In aircraft design, models are built and their flight characteristics tested in a wind tunnel. Models of missiles and less spectacular systems of transport are similarly tested. Models of ships, aircraft, and rockets help solve practical problems in design. Thus, since early times men have made models, at scales ranging from miniature to full size, as the most direct approach to exploring the characteristics of new constructions and demonstrating the three-dimensional qualities of known ones. Today, modelmaking is a highly developed profession in the service of industry, education, architecture, the military, and other fields.

Scale models of entire proposed factories are made to study locations of stock rooms, machinery, and other facilities in order to achieve maximum efficiency in production-line assembly. In its educational programs, industry uses cutaway or clear plastic models to demonstrate working relationships of the machine parts.

The study of water flow has yielded

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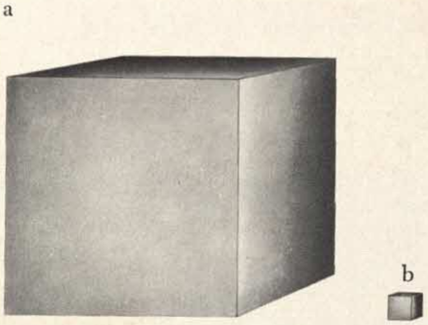

GEOMETRICAL AND MECHANICAL MODELS—The simplest type of model is a reconstruction to scale of an object.

The small cube **b** is a geometric scale model of the large cube **a.** The model was made to a scale of 1/10 by reducing all its dimensions by the factor of ten. In geometric models, the reductions apply only to linear dimensions: the angles remain unchanged. Only linear dimensions are used if the scale factor is to be respected linearly. The surface dimensions, however, have been reduced by a ratio of 1:100 and those of volume by a ratio of 1:1,000.

These facts are implicit in the construction of geometrical models and are sufficient to illustrate the sort of difficulties encountered in making mechanical models. Given the geometrical model **b,** to represent a simple cube **a** resting on the ground, if the original object and the 1/10 scale model are made of the same material, the weight as well as the volume will be reduced to a thousandth of the weight of the original. The pressure exerted on the ground by the model cube is exactly the value of the scale factor—1/10 that of the original. The complications increase with more complex objects or mechanical systems.

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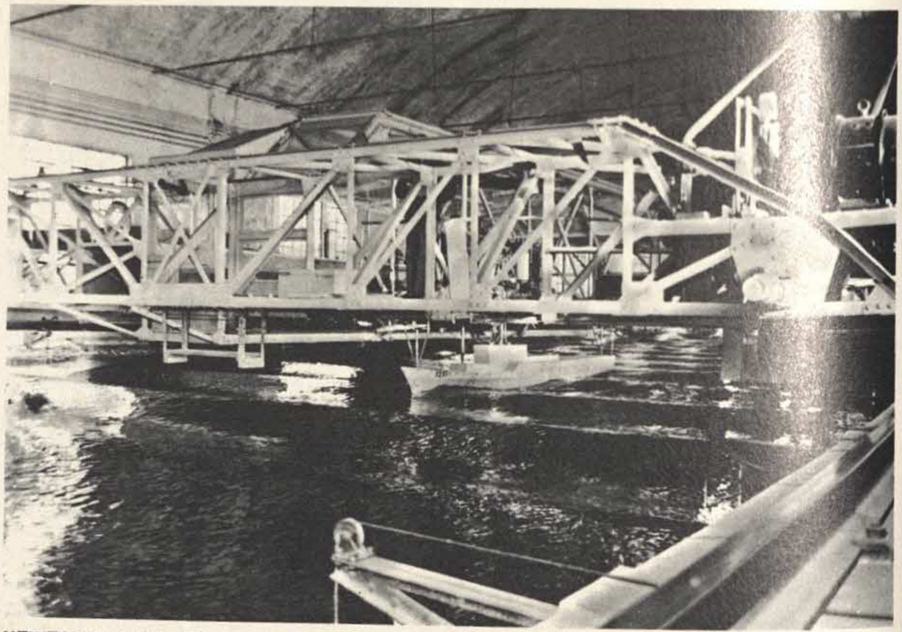

NEWTON'S LAW—Sir Isaac Newton worked out the laws for finding the scale factors of mechanical models, in which kinetic and dynamic quantities as well as geometric ones are involved. Consider a mechanical magnitude Q with dimensions $(L^{\alpha}\ T^{\beta}\ M^{\gamma})$. Newton showed that for a model of the system to which this magnitude applies, which is reduced by the factor λ, the corresponding magnitude q is reduced by the proportion given by the equation:

$$Q = \lambda^{\alpha} + \beta/2 + 3^{\gamma}q.$$

In order to design the hull of a ship and study its properties of resistance to water, a model is constructed to a scale of 1:100. It is necessary to calculate the velocity (speed) at which the model must be pulled in a testing tank to determine the performance characteristics of the actual ship. The velocity has the dimensions $V = (L^{1}T^{-1})$. Therefore, the model must be pulled at a velocity ten times less than the speed of the ship. This calculation is made for all models tested in hydraulic tanks, such as the one in the illustration. Newton's law, when applied to models of ships, is known as Freude's law.

some unusual models. One of the largest of them is a complete working model of the Mississippi River basin, which is used by the U.S. government for demonstrations and experiments in flood and channel control. Another model that served a valuable purpose in the same field was a scaled-down section of the Suez Canal. The model was used for determining exactly what pressures the banks must withstand. The model, which was 210 ft long and 29½ ft wide, was installed in a hydraulic laboratory in Grenoble, France. A self-propelled model of the hull of a tanker made hundreds of round trips through the canal until the erosion of the banks reached a maximum. As a result of these studies, an asphalt mattress poured over a framework of steel and wire mesh was designed to

POWER IN SHIPS—Newton's law may be applied to the power required to drive ships. A ship is built with dimensions exactly double in scale to a model: it will have the same form, with double linear dimensions, and the engines will be in exact proportion to those of the half-scale geometric model; that is, $2^3 = 8$ times greater. Thus, if the specific power (horsepower per unit weight of engine) is the same in both cases, the ship will be able to travel at a velocity $V = v\sqrt[3]{\lambda}$, or 1.26v. With engines enlarged to full scale, a speed 1.26 times greater can be obtained, or smaller engines can be used to obtain the same speed.

This is why the encumbrance of the engines is less in a large ship than in a small one. In addition, when the displacement of the fuel tanks on board is equal, the larger ship will have a greater range than the smaller one.

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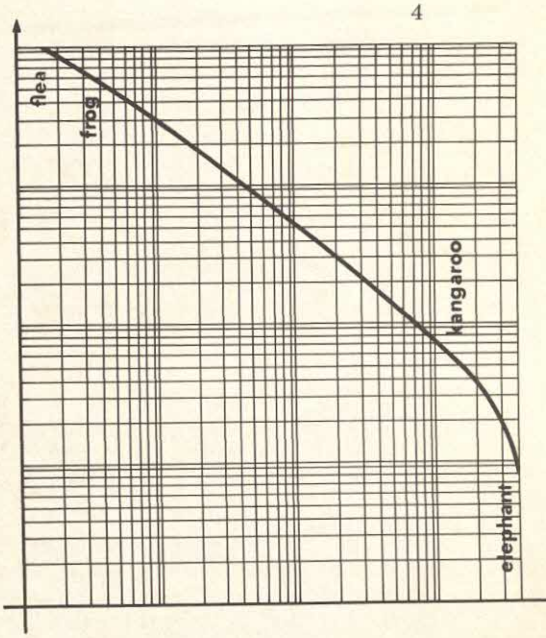
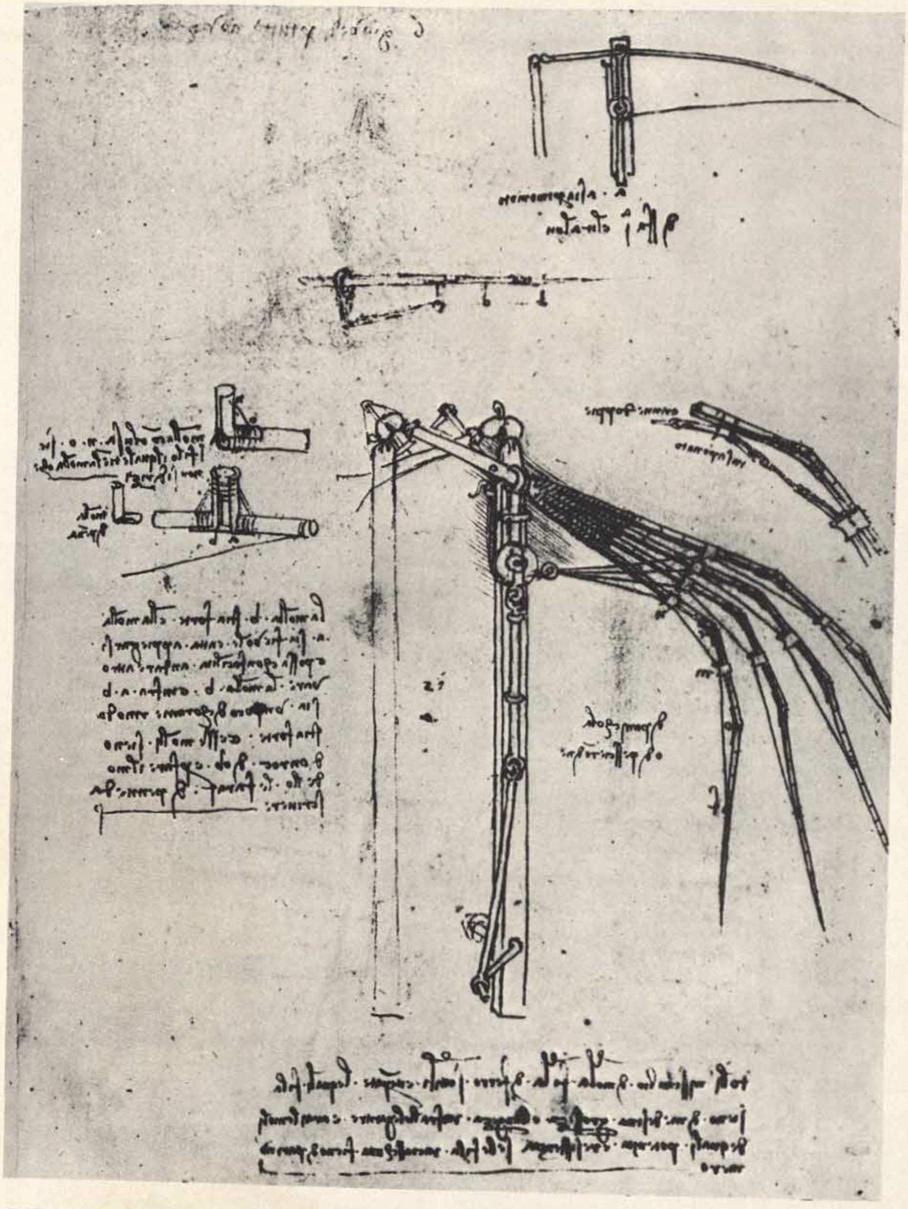


THE ACROBATIC PERFORMANCE OF LIVING CREATURES—An important factor bearing on the acrobatic performance of living creatures is suggested by the theory of models: just as the ratio between specific power and mass in a bird determines its ability to fly, so does it determine the agility of a land animal.

The graph shows the curve of the function representing the variation of acrobatic performance of animals in proportion to their size. The abscissa is on a logarithmic scale and gives the ratio between the dimensions of an animal and those of the smallest insect with a highly acrobatic performance—the flea. The ordinate, also to logarithmic scale, shows the ratio between the length of the jump of an animal and that of its body.

This graph brings two very interesting facts to light: first, the continuity with which the curve runs, and, second, the existence of a limiting point on the curve, a point corresponding approximately with the value for the elephant, which is probably the poorest jumper on Earth. The elephant's inability to jump is due to its bulk; animals of even larger size not only cannot jump but must live in water to help sustain the weight of their bodies. Even so, in most large animals muscle power is large in proportion to body size. That is why the body of an elephant is very stocky, while that of a spider or a mosquito appears almost skeletal, since very little musculature is required to produce very agile and nimble movements.



FLIGHT—When air is blown through a wind tunnel, a model aircraft inside the tunnel will be subject to forces comparable to those encountered by a real aircraft. The comparison is made by applying formulas deduced from Newton's law. Flying animals, however, present different problems. The better animal flier will be the one with the larger proportion *R* between amount of the power developed by its muscles and the weight of its body. (To consider only the strength of the animal in question is not enough; account must also be taken of the time needed to generate the wing power, which implies the concept of potential.) On the basis of Newton's theory, the ratio can be shown as $R = r\sqrt{\lambda}$.

To fly adequately, a bird of prey with a wingspan of 1 m (about 3 ft) must generate a specific power of about one-hundredth of a horsepower per kilogram of body weight. On the other hand, in an insect with a wingspan of only 1 cm (about .4 in.), or 100 times less, the specific power is reduced by a factor of 10, to as little as one-thousandth of a horsepower per kg of body weight. Thus, in insects, the factors that contribute to flight are not as critical as in the case of birds, especially in regard to lightness and the degree of musculature. Perfection in animal aerodynamics is best typified by large birds, which use their relatively meager musculature to fullest aerodynamic advantage. One exception is the ostrich, which would need several hundredths of a horsepower per kg of its own weight—that is, several horsepower—to get off the ground. The musculature of the ostrich is unable to generate such power. Nor is man able to generate this amount of power. In order to fly he would need a musculature capable of generating a total of several horsepower. Thus, even such ingenious constructions as Leonardo da Vinci's "human flying machine" are doomed to failure. The illustration shows Leonardo's sketch of his flying machine, complete with catapult engine, drawn on a page of the *Atlantic Codex*.

The comparison may be extended by considering the characteristics of aircraft, which may be thought of as large flying animals. For good performance, the horsepower-weight ratio of a 20- to 80-ton aircraft with a wingspan of 20 to 40 m (about 60 to 130 ft) must be about one horsepower per kg (about 2 lb).

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slide over the banks of the canal, eliminating some of the job of dredging.

But the theory of models can also aid in the solution of theoretical problems. Facts of anatomy and physiology alone, for example, will not explain certain behavioral phenomena in the animal world. A kangaroo is noted for its ability to jump; a seven-foot buck can bound along in 25-foot leaps. Yet the minuscule flea performs a much more spectacular feat in jumping 13 inches. If a kangaroo could jump a comparable distance, it would leap about 700 feet! Small birds and many winged insects perform extraordinary aerobatic maneuvers, while larger birds depend more on riding air currents and gliding. The use of models, originated by Galileo and developed by Newton, helps scientists understand such phenomena.

THE LIQUID-DROP MODEL OF THE NUCLEUS

an extremely heavy drop of nuclear liquid

It would be inaccurate to state that positive and negative charges exist within the atom unless it is stated at the same time that the positive charges are situated in the center of the atom, where the mass is concentrated, and that the negative charges are distributed along the periphery. In the same way, it is inaccurate to state merely that protons and neutrons exist inside the nucleus, even though this rather rudimentary knowledge enables physicists to understand some fundamental facts such as the nature of isotopes, the reason for the difference between the atoms of different chemical substances, and the reason for the atomic weights of the elements.

Advanced research in nuclear physics led to the discovery of numerous phenomena that cannot be explained merely by the knowledge that the atomic nucleus consists of protons and neutrons. The study of atomic number presents considerable difficulties, somewhat similar to those encountered when the structure of the atom was first studied. Physicists at first thought that they had discovered that the atom contained electrical charges, and that the positive charges were concentrated, along with its mass, in a very small volume at the center of the atom. Later they thought that the electrons revolved around the nucleus in circular or elliptical orbits. This hypothesis, however, ran counter to Newton's classical mechanics, which could not explain how an atom received its electrical charge. A new form of mechanics was then developed, known as quantum mechanics, which was consistent with these hypotheses.

In the case of the atomic nucleus, however, a major problem remains: the nature of the forces that maintain the protons and the neutrons in a close bond is still unknown. It is known that the force maintaining the bond between the nucleus and the electrons is a reciprocal electrostatic attraction, which is evident to anyone who rubs a plastic comb with a cloth and attracts pieces of paper to the energized comb; however, the forces that bind the components of an atomic nucleus have not been precisely identified. These forces have extremely short range; they become negligible if the distance exceeds the order of magnitude of the nuclear diameter.

THE NUCLEAR MODELS

One model for the atom has been a miniature solar system, with the electrons as the planets orbiting the nucleus as the sun. The atom is not necessarily constructed in this way, but the planetary hypothesis helps explain many properties of the atom.

When the Greek astronomer Ptolemy conceived of all the celestial bodies as revolving around the Earth, he was, in a sense, constructing a model of the planetary system and the universe—a model that explained almost perfectly most of the laws of motion of the planets, the sun, and the stars. Nevertheless, it was not perfect, and it was later replaced by the Copernican model, which conceived

THE PLANETARY SYSTEM THROUGH THE CENTURIES—The Ptolemaic System (Illustration 1a) places the Earth at the center of the universe. In the Copernican System (Illustration 1b), on the other hand, all the planets, including the Earth, revolve around the sun. Finally, the Keplerian-Newtonian System (Illustration 1c) takes strict account of gravitation.

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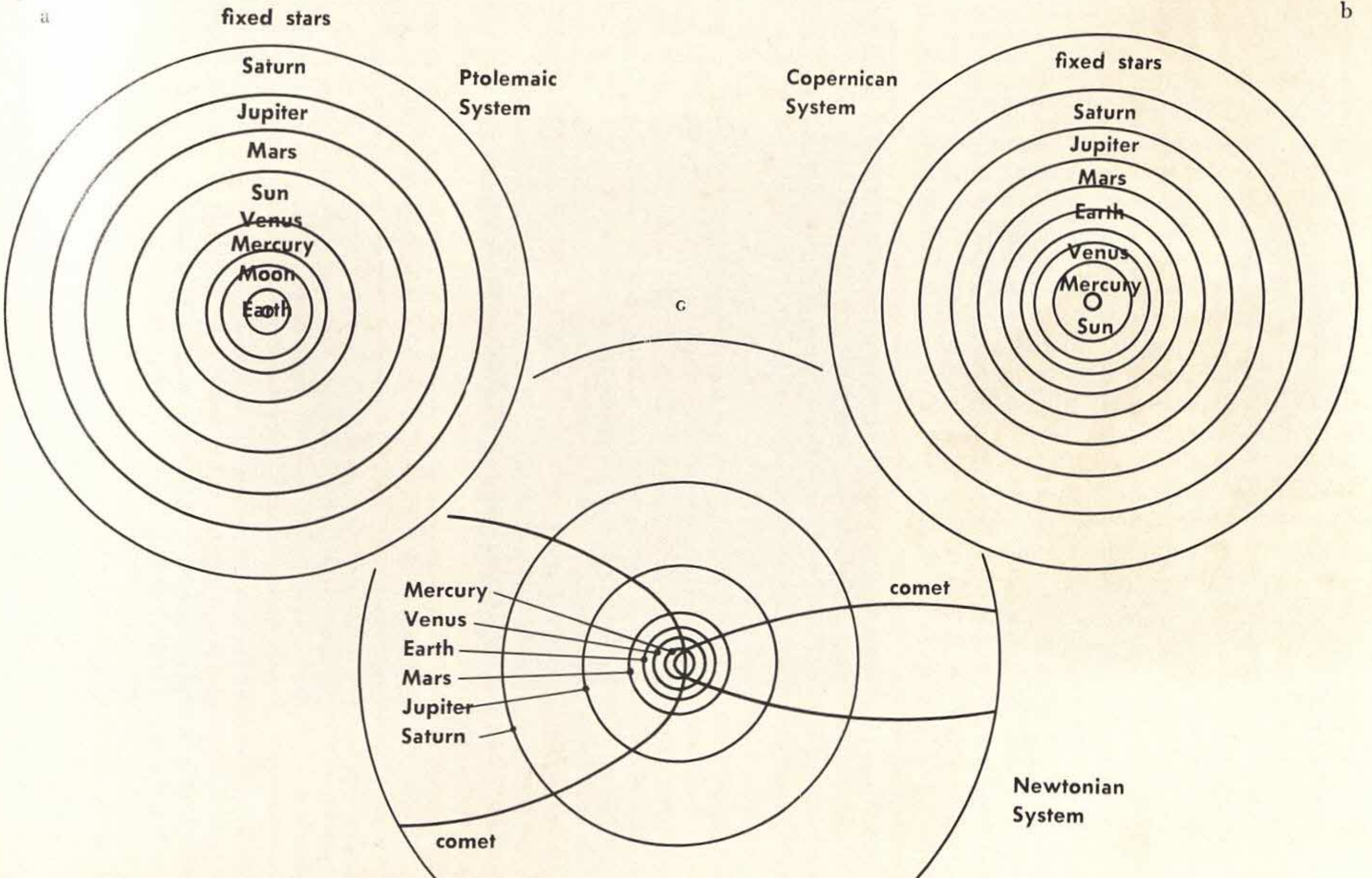


2

PTOLEMY (CLAUDIUS PTOLEMAEUS)—Astronomer and geographer and author of the first model of the planetary system, Ptolemy lived in Alexandria in the second century A.D.

of the planets revolving around the sun. Even this model is now used only in its broad outlines, because of the large number of modifications that were found necessary. In the same way, physicists have constructed many models of the atomic nucleus, each of which can explain certain phenomena better than another model. The most simple and elementary of all the models so far proposed is the so-called liquid-drop model.

THE LIQUID-DROP MODEL OF THE NUCLEUS

Protons and neutrons are known to be the only components of the atomic nucleus. It often happens that some property of the nucleus depends solely on the total number of protons and neutrons it contains—the sum of all of them combined, regardless of their proportion. In such a case, it is pointless to distinguish between protons and neutrons by name; it is more useful to designate both particles by their generic name of "nucleon."

Nucleons continue to be bound within the nucleus because they exercise forces on each other that are capable of offsetting the electrostatic repulsion of the positively charged protons. The existence of these attractive forces suggests the analogy of the attraction of the molecules within a drop of water. These molecules also attract each other, although their reciprocal attraction is much weaker than that of nucleons; the result of the reciprocal molecular attraction is a drop, in which the molecules on the outer surface are attracted by those in the interior of the liquid and thus form a kind of surface film. This film tends to contract and present a minimum surface, forming a drop, a spherical volume of liquid—because the sphere contains the maximum volume with a minimum surface area.

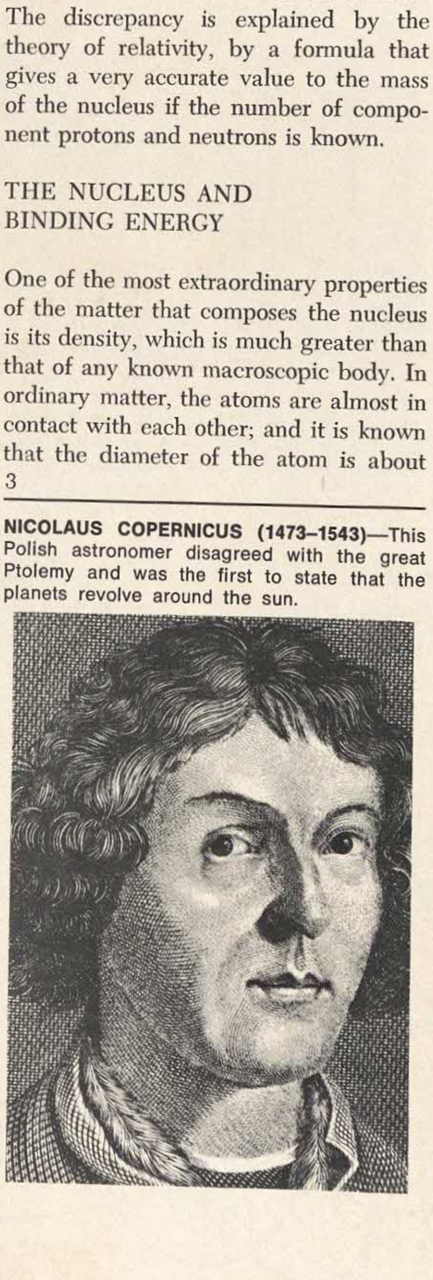
The first characteristic of the nucleus that requires explanation is its mass. It is known that the mass of a nucleus cannot be calculated simply by adding up the masses of all the component protons and neutrons; this sum will always prove to exceed the actual mass of the nucleus. The discrepancy is explained by the theory of relativity, by a formula that gives a very accurate value to the mass of the nucleus if the number of component protons and neutrons is known.

THE NUCLEUS AND BINDING ENERGY

One of the most extraordinary properties of the matter that composes the nucleus is its density, which is much greater than that of any known macroscopic body. In ordinary matter, the atoms are almost in contact with each other; and it is known that the diameter of the atom is about 100,000 times that of the nucleus. Therefore, the volume of the nucleus must be 10^{15} less than that of the atom, because the volume of any body is proportional to the cube of its diameter ($100{,}000^3 = 10^{15}$); yet almost the entire mass of the atom is concentrated within this minute volume. This may be better understood, perhaps, by analogy: if the oxygen and hydrogen nuclei of one cubic centimeter of water could be collected and tightly packed, it would form a solid that would weigh one trillion grams, or one billion kilograms, although a cubic centimeter of water weighs only one gram. In other words, one billion kilograms of matter would be concentrated in one cubic centimeter of volume, although this weight of water would normally occupy a volume of one cubic kilometer.

3

NICOLAUS COPERNICUS (1473–1543)—This Polish astronomer disagreed with the great Ptolemy and was the first to state that the planets revolve around the sun.



4

ISAAC NEWTON (1642–1727)—This English physicist and mathematician formulated the theory of universal gravitation.

A second important characteristic of nuclear matter involves the binding energy of its nucleons, which is great enough to change the actual mass of these nucleons while they are in bond. The unit of measurement of such particles is the atomic mass unit (amu), which is one twelfth of the mass of the most common carbon isotope. An individual proton weighs 1.00813 amu and an individual neutron weighs 1.0096 amu. The sum obtained by adding these two masses is 2.01773 amu; but if the two particles are bound together to form a deuteron, this combined particle has a mass of 2.01471 amu—less than the total of the masses of the two unbonded nucleons. This requires an explanation.

When the two particles are linked, the attractive force exercised between them releases energy. This is the same phenomenon that occurs when atoms of hydrogen and oxygen are linked to form a molecule of water: energy is released. But when the nucleons of the deuteron are still unlinked, this energy has not yet been released and is, therefore, contained in them in a potential state, in the form of mass. When the two particles are linked into a deuteron, the energy is released and is lost to the deuteron.

The special theory of relativity teaches that this energy, like all energy, has mass; the two nucleons linked to form a deuteron, therefore, weigh a little less than they did before they were linked. For this reason a stable atomic nucleus always weighs a little less than the total of all its component protons and neutrons.

The energy released when the nucleons are linked in the nucleus is called binding energy, and is very great. When transformed into mass, it considerably lightens the nucleus and produces what is known as mass defect. The term *defect* indicates that the nuclear mass is diminished in comparison with the sum of its component masses. (There is also a "mass defect" for water corresponding to its binding energy. However, it is very much less than the total mass of the water molecule and may be ignored.)

5

JOSEPH JOHN THOMSON (1856–1940) AND ERNEST RUTHERFORD (1871–1937) — These English physicists won Nobel Prizes for their work on atomic structure; Thomson (left) for his discovery of the electron, Rutherford (right) for ascertaining the compound nature of the nucleus and its dimensions.

THE WEIGHT OF BINDING ENERGY

The special theory of relativity states that mass (expressed in grams) is related to energy (expressed in ergs) by the formula $E = mc^2$, where c is the speed of light (expressed in centimeters per second). In dealing with the properties of nuclei, masses and energies are expressed in units other than grams and ergs; mass is expressed in atomic mass units (amu) and energy in multiples of the electron volt (ev), which is the amount of energy acquired by an electron when it increases its potential by one volt. (A familiar multiple of this unit is Mev, or million electron volts.) An energy of about 8 Mev is released each time a new nucleon is introduced into a nucleus; this energy is equivalent to about one one hundredth part of the mass of the nucleon.

The nucleon, therefore, weighs less inside the nucleus than it weighed when it was outside the nucleus. This may appear paradoxical, but it has been verified experimentally.

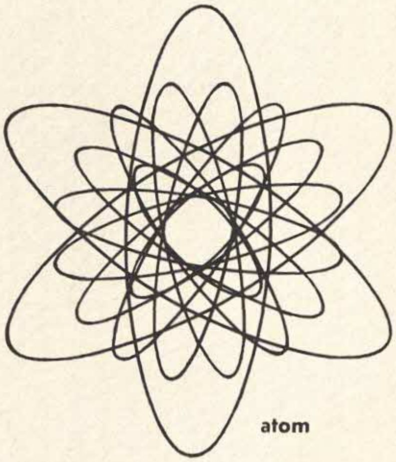
HANS ALBRECHT BETHE (1906–)—The name of this German-American physicist is linked with various formulas and the nuclear processes that occur in the sun. He contributed to nuclear physics many studies on the binding energy of nucleons and on artificial disintegration.

6

THE MODEL OF THE ATOM AND THE LIQUID-DROP MODEL OF THE NUCLEUS—The atom (left) is shown as a miniature solar system in which the electrons revolve around the nucleus in elliptical orbits of different dimensions and different planes.

The nucleus (right), on the other hand, contains the nucleons much as a drop of water contains its molecules; in both cases, attractive forces between the particles ensure that the drop will assume spherical form as long as it is in equilibrium, because the sphere is the form that contains the maximum volume within a minimum surface area.

7a



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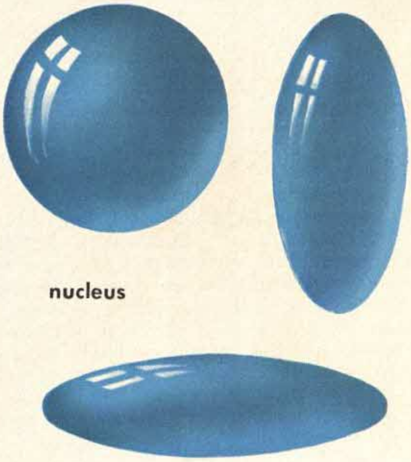


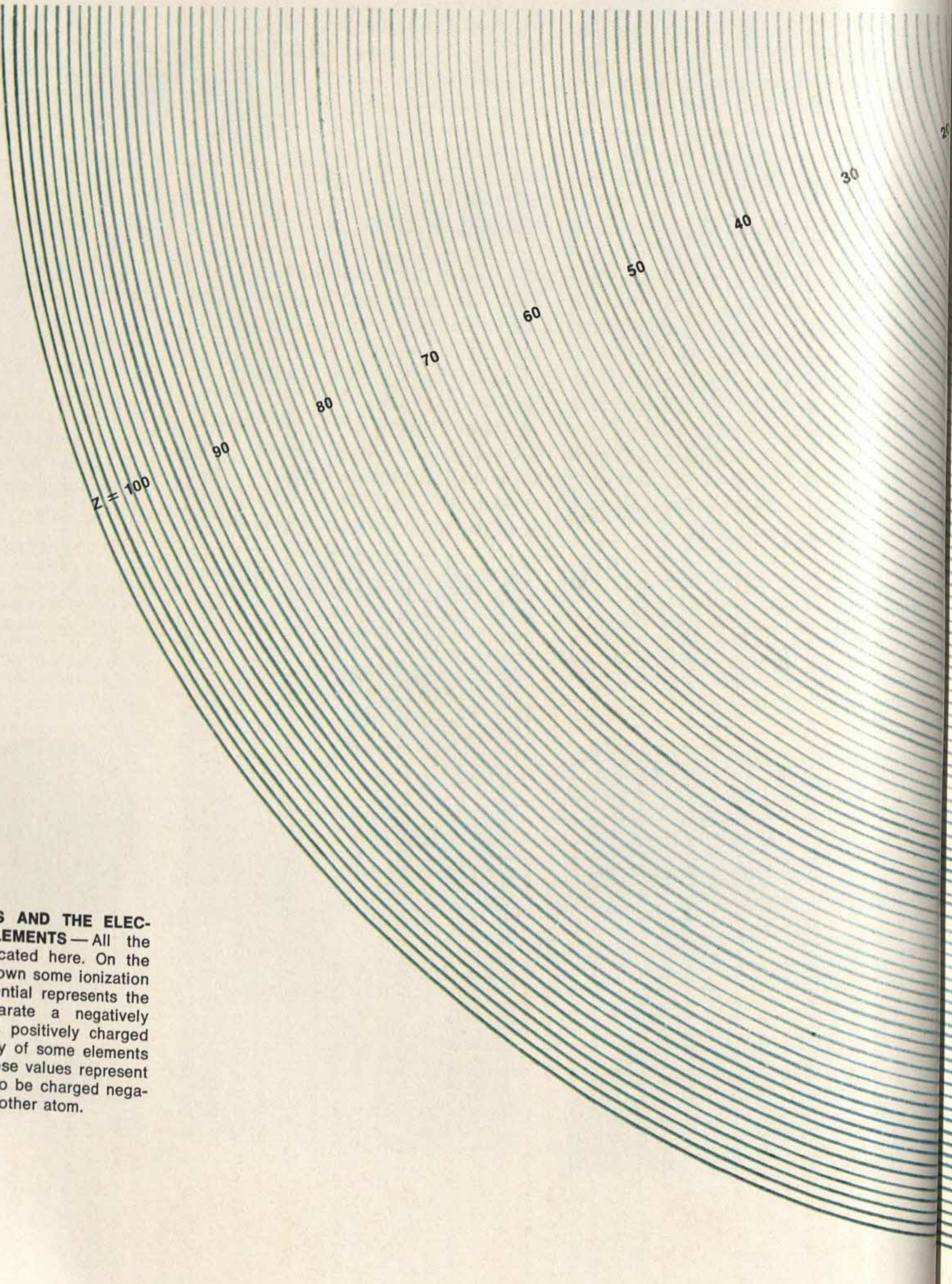
PERIODICITY OF ELEMENTS

electrons as classifiers

As early as the fifth century B.C., Greek philosophers concluded that the world was made up of countless minute particles that they called atoms, meaning indivisible. The concept that the atom was the smallest indivisible particle of a substance persisted until late in the nineteenth century, when scientists laid the groundwork for the modern theory of atomic structure. Finally, in 1897, J. J. Thomson discovered the electron, and the atom was no longer "indivisible."

To understand the periodicity of elements, one must have a knowledge of atomic structure: that is, he must know why apparently different elements have similar characteristics and properties. An atom, scientists say, consists of a positively charged nucleus surrounded by negatively charged electrons. If that were the whole story, the electrons would be attracted by the nucleus and eventually fall into it. The reasoning goes this way: because electrons move around the nucleus, and because electric charges emit energy when they move, is it not logical to conclude that electrons, which lose energy as they rotate, will slow down and descend into the nucleus, thus destroying the atom?

1

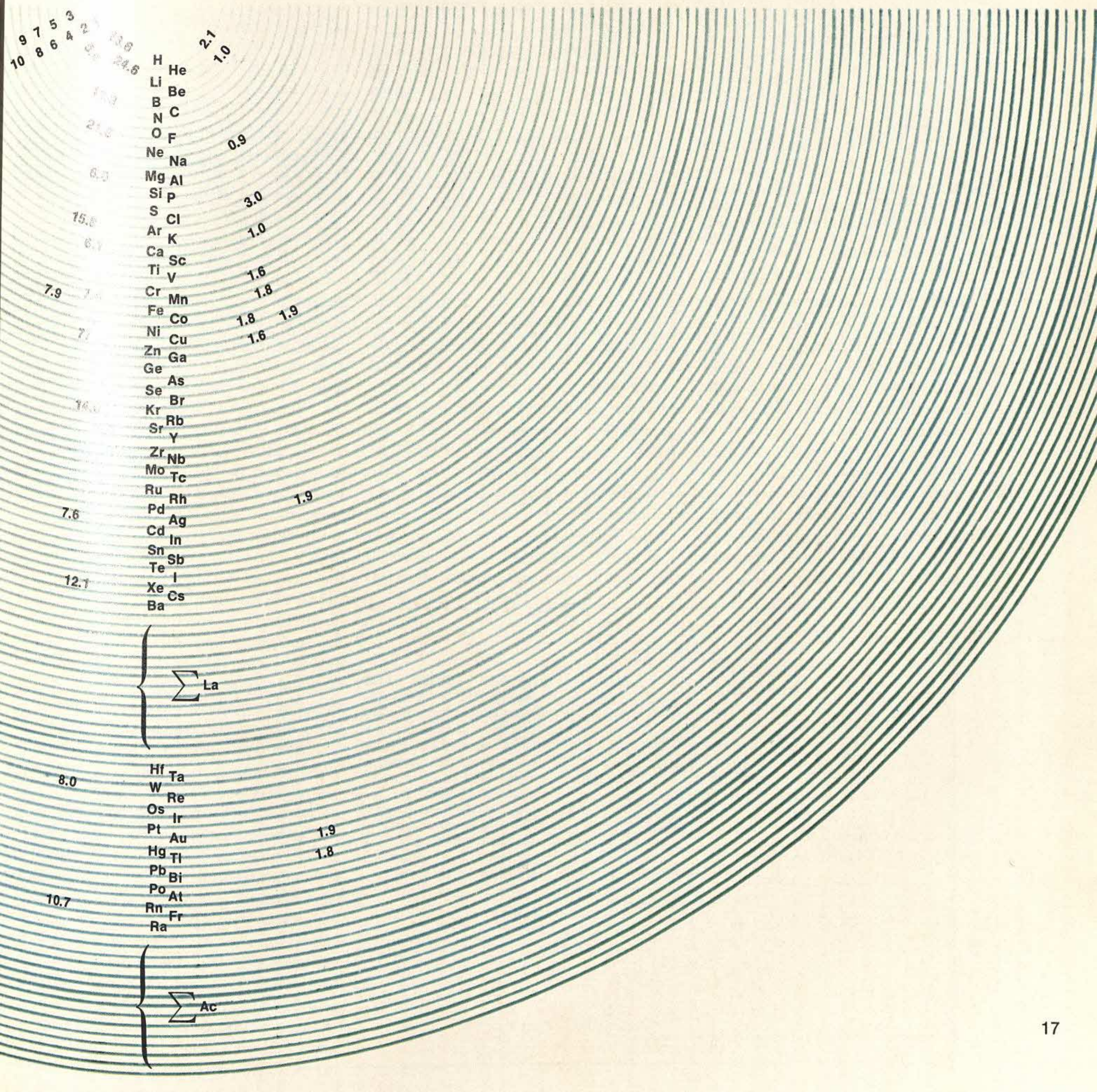


IONIZATION POTENTIALS AND THE ELECTRONEGATIVITY OF ELEMENTS—All the known elements are indicated here. On the left of the symbols are shown some ionization potential values. The potential represents the work necessary to separate a negatively charged electron from its positively charged atom. The electronegativity of some elements is shown on the right. These values represent the tendency of an atom to be charged negatively when attached to another atom.

But this does not happen, a fact that caused confusion until 1913, when the physicist Niels Bohr concluded that the kinetic and potential energy (whole energy) of electrons can only take on fixed values. Bohr's work confirmed a series of spectroscopic experiments that suggested a noncontinuous distribution of energy in atoms. Electrons in an atom, it was decided, have fixed energy values, and variations in the energy can take place only when the electrons pass from one energy level to another. This is not a gradual passage; it is a jump from one level to the other. The result: if the electron has no lower level to jump to, it does not emit energy. Electrons that rotate in the lowest energy level—and are therefore closest to the nucleus—have no levels below them; therefore, they will continue to rotate without dissipating energy and without falling into the nucleus.

To sum up: the emission of energy takes place only when an electron jumps from one level to another below it. And energy must originate from outside the atom in order to produce a jump from a lower to a higher level.

Electrons do not obey the classical laws of electrodynamics. They obey new principles, of which the most important is that electrons in an atom can only occupy particular energy levels. These levels are labeled 1, 2, 3, and so on, from the bottom (the level nearest the nucleus) upward. The number of the energy level in question is marked with an n and is called the chief quantum number. The number of electrons that can occupy the same energy level is always equal to $2n^2$. Electrons in the $n = 1$ level



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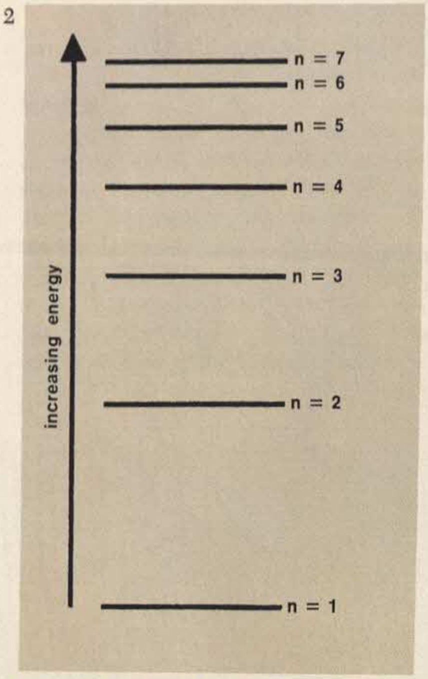


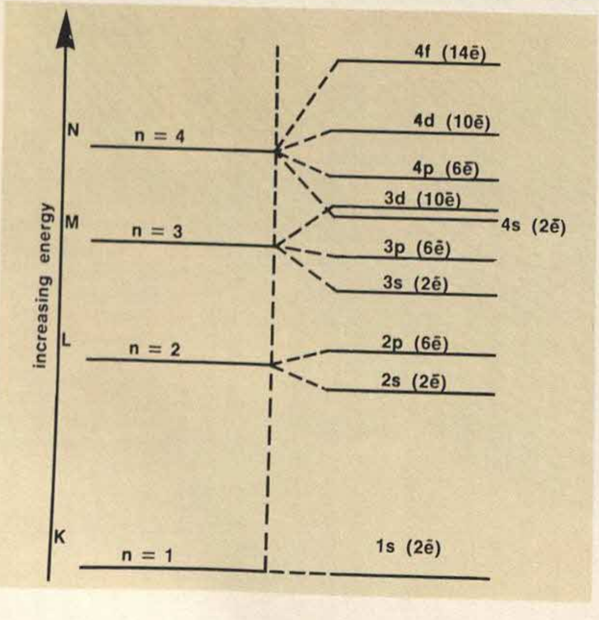
ELECTRON ENERGY LEVELS IN AN ATOM— Various electrons occupy various energy levels. The bottom line (n = 1) is the minimum energy level, where the maximum energy is required to expel the electron from the atom.

(two of them) are said to belong to shell K, the innermost shell. Because these electrons feel the attraction of the nucleus at its strongest, it is extremely difficult to make them jump to outer shells. The electrons in the $n=2$ level are in the shell L, and so on.

It is impossible for electrons to have energies halfway between the various energy levels. Illustration 1 shows the levels that electrons can occupy for growing energy values: as the energy increases, the distance between levels decreases. This means that the more mobile electrons will automatically be those in the outer shells, because less energy is required to make the jump between them than between other levels. These electrons are *valence* electrons and are involved chiefly in chemical bonds.

The fact that many of the properties of atoms depend on valence electrons, and that there is a limit to the number of electrons that can occupy any one energy level, accounts for the periodic repetition of many properties among elements that at first sight seem different. It is substantially the atomic structure that determines the similarities, differences, and other specific constants of individual elements.

The electrons in any one shell have substantially the same energy, although spectroscopic examination has shown that every energy level is made up of various sublevels that exist in extremely close proximity. The number of these sublevels is equal to the chief quantum number (n) of the level. Thus, shell M ($n=3$) contains three sublevels. The sublevels usually are labeled s, p, d, and f, starting from the sublevel with the lowest energy. The shell N ($n=4$), for example, has four sublevels: 4s, 4p, 4d, and 4f. Illustration 3 shows the principal energy levels and the corresponding sublevels for the first four shells. Note that as the chief quantum number increases, sublevels belonging to different shells overlap. For example, sublevel 3d is at a higher energy level than sublevel 4s, which belongs to the shell above. Such examples help explain oddities in the periodic table of elements. The atomic model discussed here—a nucleus and several shells with fixed energy levels—is only one of the various models in existence. However, it is the most convenient.



3

ENERGY LEVELS AND SUBLEVELS — Electrons belonging to the same energy level should have the same energy, but this is not always true, because every level is made up of sublevels where the energy varies very slightly. The maximum number of electrons that any one sublevel can obtain is given in parentheses.

THE IONIZATION POTENTIAL OF ATOMS

Another constant factor typical of all elements is their *ionization potential*. In the case of two or more elements with different ionization potentials, these simple values can be used to forecast the way in which the elements will behave. Using the smallest metallic atom, lithium (Li), as an example and separating an electron from the neutral atom gives:

$$\text{Li} \rightarrow \text{Li}^{+} + \text{e}.$$

The reaction produces a positively charged ion; or, to put it another way, the atom has been ionized. Obviously, this reaction entails a change in the energy. This particular energy is called the ionization potential and represents the work necessary to separate the negatively charged electron from the positively charged atom. This potential can be measured with special techniques and is given in electron volts (1 electron volt $=3 \cdot 8 \cdot 10^{20}$ calories). The lower the ionization potential, the easier it will be to ionize the atom. The ionization potential grows as the nuclear charge increases, because the force of attraction between the nucleus and the electrons increases. The potential also increases as the size of the atoms decreases because the smaller the atom, the closer the electrons will be to the nucleus and the harder they will be to separate. In the case of atoms with outer shells with their full complement of electrons (such as the rare gases neon and argon), the ionization potential is high because it is very difficult to break the electronic saturation.

The electronegativity scale of the elements also is important in the study of the similarities and differences between elements. The values on this scale show the tendency of an atom to be charged negatively when attached to another atom—that is, the tendency of an atom to attract bond electrons. If the electronegativity values are known, it is possible to forecast what sort of bonds will be formed between two reacting atoms. For example, sodium (Na), which has an electronegativity value of 0.9, will react with chlorine (Cl), which has an electronegativity value of 3, to form an ionic bond. Because the electronegativity value represents the tendency of an atom to attract electrons, this tendency will be enormous in chlorine, which has a value near the maximum (4, for fluoride). The chlorine will be ionized into Cl^{-} by taking an electron from the sodium, which in its turn will be ionized into Na^{+}.

THE MASS OF THE ATOM | nuclear mass is the key

How much does an atom weigh? Obviously the weight of an atom is extremely minute—at least when compared with the weight of an object that is large enough to be visible to the naked eye. Each visible object, no matter how small it may be, is made up of an incredible number of atoms. If, for example, a microscopic drop of water is allowed to evaporate from the surface of a clean glass crucible, it will leave a small stain produced by the salts that are dissolved in ordinary water. Although such a stain may weigh no more than a fraction of the millionth part of a gram, it will still be visible to the naked eye; and yet even this tiny stain can contain more than 10 trillion atoms.

An atom thus has a very minute weight that can be expressed in terms of fractions of a gram, but this method of weighing atoms is not useful for the practical purposes of chemical calculations. For such calculations it is much better to use a unit that is directly derived from the atom itself—a unit related to the atomic nucleus. To understand how this unit of weight is defined, some knowledge of the structure of atoms and nuclei is necessary.

HOW ATOMIC NUCLEI ARE CONSTRUCTED

The structure of the hydrogen atom shows that it, like all other atoms, is composed of a nucleus and one or more electrons orbiting around this nucleus. In the case of hydrogen only one electron is in orbit. Three types of nuclei are capable of maintaining a single electron in orbit to thus form a hydrogen atom: a nucleus consisting of a single proton, which is the most common hydrogen nucleus; a nucleus consisting of a proton and a neutron, thus giving rise to the deuterium nucleus; and last, the tritium nucleus that consists of one proton and two neutrons. The capacity of the hydrogen atom for combining with other atoms, as well as the properties of the resulting compounds, depends exclusively on the fact that only one electron revolves around the nucleus. The fact that the nucleus has a different mass when it contains one or two additional neutrons does not have any effect on the chemical properties of hydrogen. In fact, chemical properties depend on the number of orbiting electrons. The hydrogen atom has only one such electron because a nucleus that contains only one proton (only one particle with a positive charge) can keep only a single electron in its immediate neighborhood.

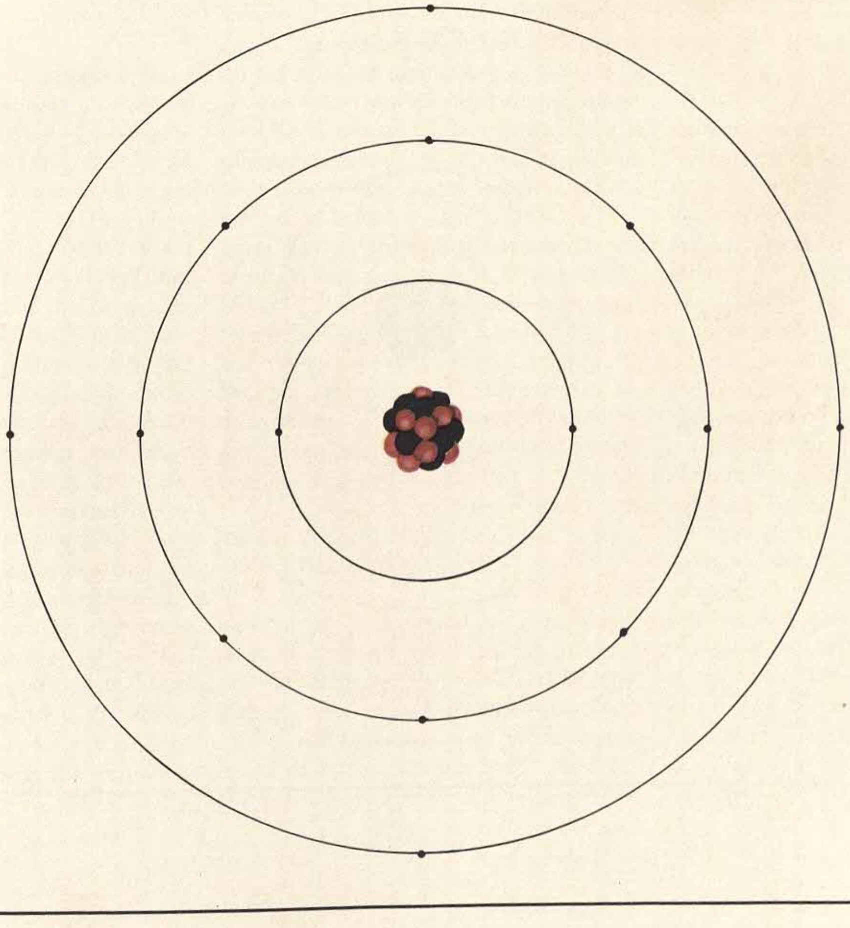
Atoms of other elements are constructed in accordance with rules similar to the one that governs the simple structure of hydrogen, and these can be listed as follows:

The chemical properties depend on the number of electrons that revolve around the nucleus.

The atoms of every element differ from

THE SILICON ATOM—By observing the structure of this atom, the rules that usually govern the structure of all atoms can be verified. The silicon nucleus is formed by 14 protons (represented by red spheres) and 14 neutrons (black spheres). An equal number of electrons revolves around the nucleus; more precisely, 2 electrons in the first orbit, 8 in the second, and 4 in the third.

1a



those of other elements because the electrons differ in number.

The number of electrons to be found in each atom is equal to the number of protons in the nucleus, because each positive charge of a proton is capable of attracting and maintaining in orbit only one electron.

Atomic nuclei of each element contain the same number of protons but may contain a different number of neutrons; yet these nuclei maintain identical numbers of electrons in orbit around themselves. Atoms of such nuclei behave in the same way chemically. Such variant atoms are isotopes (Illustration 1b) of the same element. This name is derived from the Greek *iso* ("the same") and *topos* ("place"). Isotopes are elements that occupy the same place in the table of elements.

Because the mass of an electron is almost 2,000 times less than the mass of a proton, the mass of an atom depends essentially on the mass of the nucleus, the mass of the electrons contributing only slightly to the total mass. Because the nuclei are composed of protons and neutrons (two particles having almost identical mass), as a first approximation, the mass of each nucleus (and therefore of each atom) may be regarded as a multiple of the mass of the proton or the neutron.

Alternately, and this really amounts to the same thing, the mass of any atom can be considered a multiple of the mass of the ordinary hydrogen atom, which consists of a single proton, the electronic mass being neglected for the moment. There is a view that protons and neutrons are two different charge states of the same entity—the *nucleon.*

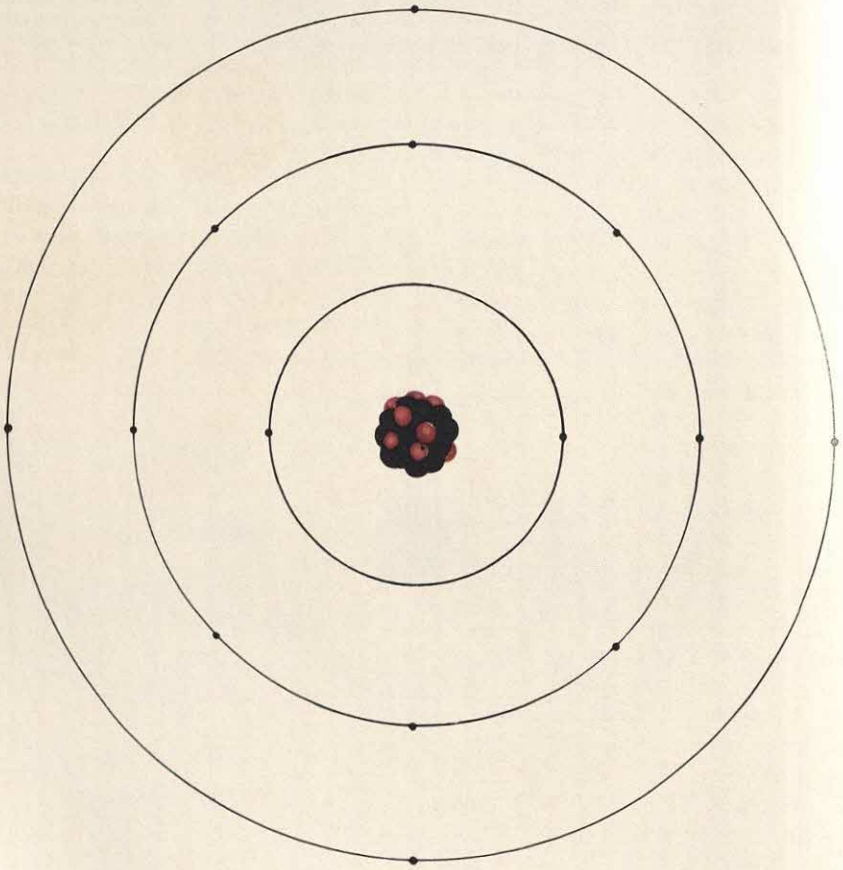
MASS DEFECT

Except for the nucleus of ordinary hydrogen, all atomic nuclei contain protons as well as neutrons. In the great majority of nuclei the number of neutrons is either equal to the number of protons or slightly greater. A nucleus of ordinary iron, for example, contains 26 protons and 30 neutrons; the nucleus of the most common isotope of oxygen found in nature contains 8 protons and 8 neutrons.

The neutrons and protons that make up a nucleus are particles of fundamentally different characteristics. While the neutrons are devoid of any electric charge, the protons have a positive charge, and it will, therefore, be more difficult to bring them close together because particles with like charges tend to repel each other. However, all this is true only up to a certain point. In nuclear

A SILICON ISOTOPE—This structure also represents a silicon atom. The number of electrons is once again 14; the chemical properties, which are known to depend only on the number of electrons, therefore, are the same as those of ordinary silicon. The isotope, however, has a different nucleus: it still contains the same number of protons (14), but there are 18 neutrons. The only difference, therefore, lies in the mass number, *A*. (A = protons + neutrons).

1b



physics one often comes across facts that could neither be suspected by nor explained in terms of the traditional concepts of classical physics. In this particular case it has been found that all the elementary nuclear particles, quite independently of whether they do or do not possess an electric charge, exercise a strong attraction on each other when the distance between them becomes very small, say of the order of 10^{-13} cm. At this proximity nuclear forces come into play, although the nature of these forces is not yet clearly understood. Because of these forces two or more protons strongly attract each other as soon as the repulsion force that manifests itself at distances of more than 10^{-13} cm has been overcome, and at this point protons are similarly attracted by neutrons. When mixed in proportions not exceeding certain limits, the particles group together to form atomic nuclei.

The mechanism by which a proton enters into the structure of an already existing nucleus and is then added to the original aggregation of protons and neutrons may be compared to a ball (the proton) that has to be rolled up a rising slope (the repulsion of the other protons to be overcome) that ends about 10^{-13} cm from the edge of a well. At the edge the ball dives into the well (attractive nuclear forces), and the proton joins with the other protons and neutrons already united in the nucleus.

The task of a neutron approaching a nucleus is somewhat simpler; it may be likened to a ball rolling along a horizontal plane until it reaches the edge of the well, at which point it joins the other members of the nucleus.

Various nuclei have thus been formed by the union of protons and electrons, and energy is liberated as this phenomenon occurs. The attractive forces have caused the particles that compose the nucleus to "fall" on top of each other. The original nucleus consisted of rapidly moving particles; the energy associated with the motion of these particles subsequently escaped from the nucleus in the form of electromagnetic radiation of very short wavelength (gamma radiation). In the process of forming the nucleus the particles have thus lost energy when compared with their free state.

The theory of relativity states that energy has mass; an energy of 25 million kwhr has a mass of 1 g. The tiny amount of energy liberated during the formation of a nucleus is the equivalent of an infinitesimal fraction of a gram; but this mass, nevertheless, corresponds to an appreciable fraction of the mass of the nucleus that has been formed. When specific numbers of neutrons and of protons are put together so as to form a nucleus, therefore, the mass of the nucleus is slightly less than the sum of the masses of its components. The difference between the two masses is the mass "defect." As a result of this phenomenon the masses of the atoms are not integral multiples of the mass of the proton and the neutron.

THE PHYSICAL SCALE OF ATOMIC WEIGHTS

A logical way of measuring atomic weights would be to use as a measuring unit the mass of the proton or the neutron. Unfortunately, these are not exactly the same, and the choice of either one would lead to fractional values of atomic mass. Mass defect would further complicate the number that expresses these weights.

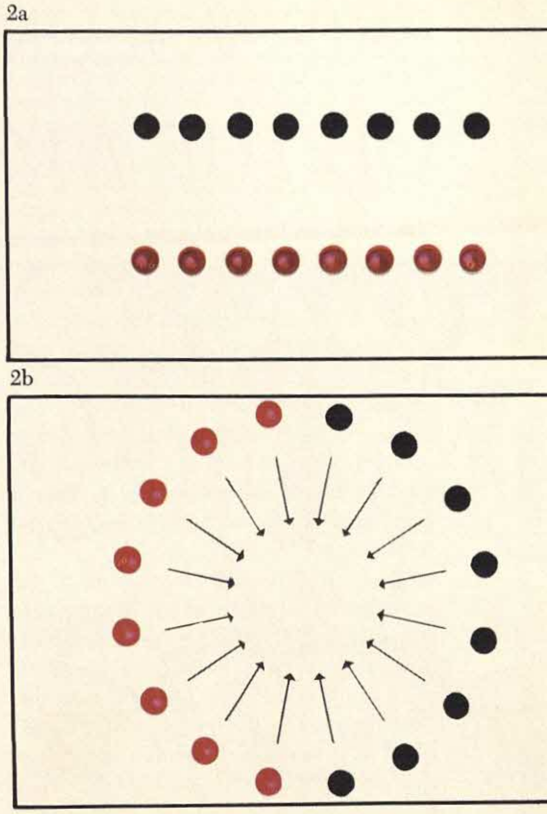
It was therefore found best to adopt a unit of atomic mass equivalent to one sixteenth of the mass of the oxygen nucleus consisting of 8 protons and 8 neutrons; that is, the isotope known as oxygen-16. This unit of atomic mass is the unit of physical mass.

Why did the choice fall on one sixteenth of the oxygen nucleus? The reason is that oxygen combines with almost all the other elements and so provides a direct comparison for determining atomic weights. Suppose it is known that 16 g of oxygen combine with 40.08 g of calcium in a compound where each atom of oxygen is linked with one atom of calcium. This means that the atomic weight of each calcium atom is 40.08 on the physical scale. A simple chemical experiment thus provides the key to knowing the atomic weight of an element. As oxygen combines very readily with almost all the other elements, a very simple means of determining their atomic weights is possible.

THE CHEMICAL SCALE OF ATOMIC WEIGHTS

Oxygen—as it is found in nature and used in chemical reactions for the purpose of comparing its atomic weight with that of other elements—does not consist exclusively of atoms with nuclei made up of exactly 8 protons and 8 neutrons (oxygen-16); it also contains small quantities of 2 isotopes whose nuclei consist of 8 protons and, respectively, 9 and 10 neutrons. When nineteenth-century chemists began to compare the atomic weight of oxygen and other elements, they did not realize that the oxygen they were using was a mixture of isotopes of different mass. So they chose their unit of mass as one sixteenth of the mass of the naturally occurring mixture of oxygen isotopes (99.76 percent of O-16, 0.04 percent of O-17, and 0.02 percent of O-18). This unit is called the unit of chemical mass.

In 1961 the International Union of Pure and Applied Physics and the International Union of Pure and Applied Chemistry, with a view to unifying the physical "standard" and the chemical "standard," decided to adopt a new unit of measurement for atomic mass (weight); their choice fell on one twelfth of the mass of an atom of carbon-12, which has 6 protons and 6 neutrons. Neither the oxygen nor the carbon standard, however, allows atomic mass to be expressed in whole numbers.



"CONSTRUCTING" AN OXYGEN ATOM— Eight protons and 8 neutrons (Illustration 2a) are required to constitute the oxygen nucleus. Attractive forces (Illustration 2b) cause the particles to "fall" on top of each other to form the nucleus of an oxygen atom.

THE VOLUME OF THE ATOM

the interplay of electric charges

The atom and the universe have this in common: their dimensions—infinitesimally small on one hand, awesomely huge on the other—boggle the mind. Yet the atom is not so small that its size cannot be measured. In May, 1970, a University of Chicago scientist announced the development of a technique for seeing individual atoms within a molecule, describing the technique as a step toward the "Holy Grail" in the field of electron microscopy.

Measuring the size of an atom is not as difficult as it might seem. The problem is much like that of measuring the diameter of shot without a suitable instrument such as calipers or a micrometer. Measurement is still possible. For example, a pint bottle can be filled with identical shot that are then counted. This is a rather laborious method—and one not completely accurate—but yields at least an order of magnitude for the volume of each spherical shot, making it simple to calculate the diameter.

The same principle is used in measuring the size of atoms. Laws of chemistry enable scientists to calculate the number of atoms contained in a certain volume of matter. The volume is then divided by the number of atoms it contains, with allowance for the fact that atoms are spherical and not cubical.

When the atoms are arranged in some regular pattern to form a crystal, other and more precise methods of measurement are adopted. The dimensions of atoms are measured in terms of an extremely small unit, the Ångström (Å). One Ångström equals one ten-millionth of a millimeter, or one ten-thousandth of a micron. The diameters of the smallest atoms are little more than 1 Å; the diameters of the largest reach 5 Å.

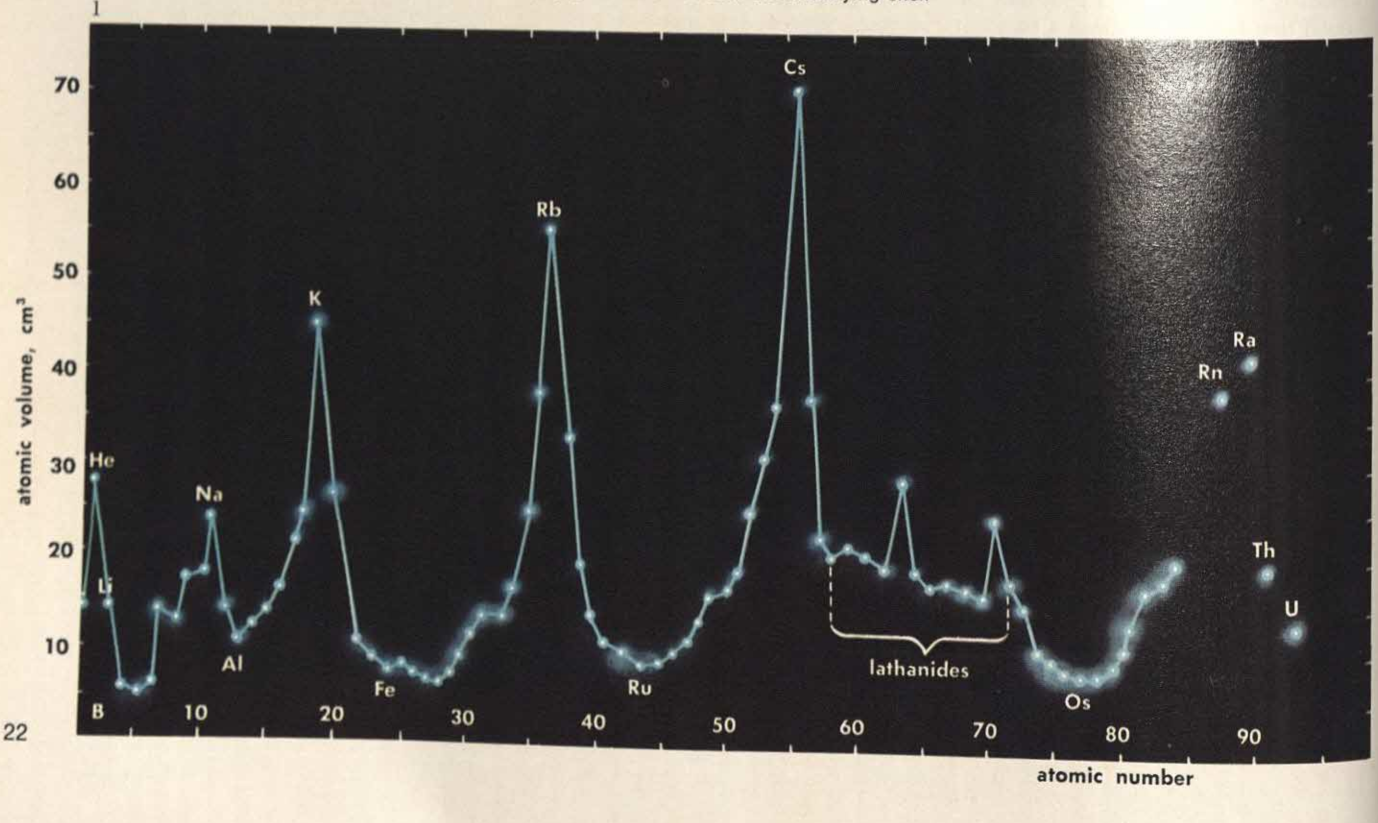
ATOMIC VOLUME AND ELECTRON ARRANGEMENT

A detailed explanation of why electrons are arranged in a certain manner around the nucleus of an atom is not necessary here. It is sufficient to examine how the electrons are arranged, because the laws of this arrangement enable scientists to interpret the laws of chemistry.

Physical laws determine how many electrons can be arranged in each layer (or orbit) around the nucleus and determine that the electrons are divided among various sublayers. The innermost of these layers is called the K layer, and subsequent layers are designated L, M, N, and so forth. As a rough approximation, these layers can be thought of as spherical shells, with the diameter of the outermost shell as the dimension of the atom.

Dimensions vary from one atom to another, depending on various factors. For example, the dimensions increase as the number of layers (or shells) increases. Because each layer can accommodate only a certain number of electrons, the number of layers will increase as the number of orbiting electrons increases.

THE RELATIONSHIP BETWEEN ATOMIC NUMBER AND ATOMIC VOLUME—Atomic volumes vary with the atomic number; more precisely, the values increase and decrease in a periodic manner. The elements with the largest atomic volumes are the alkali metals (sodium, potassium, rubidium, and cesium). Each of these elements has a solitary electron revolving in its outermost layer at a comparatively great distance from the underlying shell with its full complement of eight electrons. This causes the large dimensions of these atoms. Points in the curve correspond to the atomic number of these elements.



Conversely, for any given number of layers, the dimensions of the atom will diminish as the nuclear charge increases. An increase of the charge also increases the force of attraction that the nucleus exercises on the electrons, and the electrons arrange themselves in tighter layers; that is, the layers become closer to each other and their overall dimension diminishes. Each atom has characteristic dimensions, each different from those of all other atoms.

THE ATOMIC VOLUMES OF THE ELEMENTS

A diagram can be made to illustrate the variation of the dimensions of the atoms by drawing a horizontal line and dividing it into 92 or more equal segments. Each of these segments will correspond to an atomic number. For example, the sixth segment will correspond to the atomic number of carbon, the eleventh segment to the atomic number of sodium, and so forth. Above each segment a small circle is drawn in such a position that its distance from the base is proportional to the volume of the atom being considered. In choosing between representing the diameter of the atom or representing its volume, it is preferable to choose volume because variations of volume are greater than those of diameter. If two atoms have respective diameters of 2 Å and 3 Å, for example, this could be represented by two circles placed 2 and 3 cm above the base line—not very far apart. On the other hand, if the volumes of these two atoms are represented, the ratio between the two volumes is 8 to 27. Because 27 is more than three times 8, the two circles would be much farther apart than if the representation had been one of diameter.

Illustration 1, which shows atomic volumes arranged in ascending order of atomic number, calls attention to an interesting phenomenon. It seems reasonable to expect that atomic volumes would be quite different from each other—as indeed they are—and also, perhaps, that these volumes would be distributed somewhat at random. However, the diagram shows that the volumes vary in a regular manner. Just as the chemical properties of the atoms have a periodic pattern, so atomic volume also varies with similar periodicity.

The elements that have the largest atomic volumes—that is, the elements corresponding to the peaks of the curve that unites all the points plotted on the diagram—are the alkali metals.

The atoms of alkali metals are formed by many electrons, all revolving around the nuclei and arranged on various layers. Each layer except one is full. The outermost layer of each atom contains only a single electron. This solitary electron is responsible for the large dimension of the atom; the electron orbits at a comparatively great distance from the next shell, which has a full complement of electrons. The exception is the innermost layer, complete with only two electrons.

When eight electrons are together on the same layer around the nucleus, they form a very stable structure that presents particular properties. For example, it is very difficult to remove one of these electrons from the atom. Furthermore, these eight electrons form a most effective screen around the charge of the nucleus, making it extremely difficult for other electrons to become attached to the atom. Elements with this characteristic are known as the inert gases (helium, neon, argon, krypton, xenon) because they are not prone to react with other elements; that is, they have no tendency either to lose or to acquire electrons as they would have to do in order to form compounds.

ATOMIC VOLUME AND SPECIFIC GRAVITY

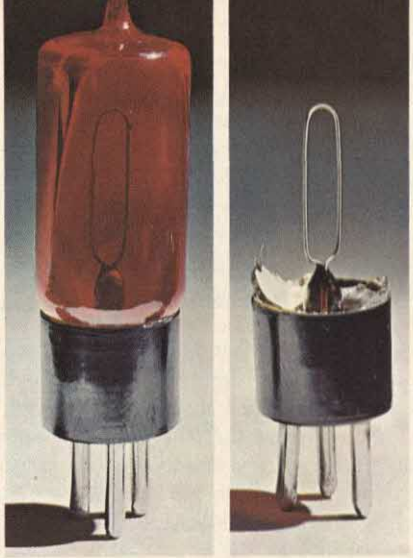
Atoms that have a high atomic number and their corresponding nuclei are generally referred to as the "heavy" elements. This term is only partly correct, in the sense that these atoms are heavier than the atoms of the so-called light elements—those elements having a low atomic number. The term is also incorrect in another sense: a piece of matter consisting exclusively of one such heavy element will not necessarily be "heavy" in the sense of having high density or high specific gravity.

The specific gravity of a body (specific gravity = weight/volume) depends partly on the weight of the individual atoms of which the body consists and partly on the volume of these atoms. (The weight of the atoms depends essentially on the weight of their nuclei, because the outer electrons are very light in weight.)

For example, the weight of an atom of cesium (Illustration 2) is approximately 132 units of atomic mass, about 2½ times the weight of an iron atom (Illustration 3), approximately 55 units. However, the diameter of an iron atom (2.52 Å) is much smaller than the diameter of a cesium atom (5.40 Å). In solid iron the atoms are much closer together than in solid cesium, so the iron has a greater specific gravity than does cesium (7.86 as against 1.87).

IONIZATION

An atom can lose one or more of its electrons. The electrons are bound to the nucleus of the atom by electrostatic attraction; to remove an electron, a force must be exerted to overcome this attraction. An electron can be removed from the atom by supplying an external force (or energy) that is equal to or greater than the force that binds the electron to its nucleus. This energy can be either ther-



2

CESIUM AND IRON—Illustrations 2 and 3 show these elements in two present-day applications: cesium as part of a photoelectric cell, and iron used to form the flowing curves of an artistically wrought gate. Although cesium has a much greater atomic weight than iron, its specific gravity is much less. This phenomenon is essentially due to the different atomic volumes of the two elements.

3

mal energy, or purely mechanical energy, the latter involving a violent collision between two or more atoms. Light can also be used to detach an electron from its nucleus. An electromagnetic radiation of frequency f has an energy given by the formula $E = hf$, where h is Planck's universal constant. When the frequency of light is such as to make E (the energy associated with the radiation) equal to or greater than the energy with which the electron is held in position, the light becomes capable of detaching the electron.

An atom that has lost or acquired one or more electrons is said to be ionized. The work that must be performed to detach the electron is called ionization work or ionization potential, and is measured in electron volts (ev).

Once an electron has been detached from an atom, a second electron can be detached from that atom. (Strictly speaking, the second will be detached from an ion.) The energy necessary to detach this second electron will be greater than that needed to detach the first, because the atom has been left with an excess of positive charge and can thus hold its remaining electrons more firmly than it could before.

An atom that has lost one of its electrons is called a positive ion; such an atom is usually represented by the chemical symbol for the element followed by a plus sign (+) written above the symbol. For example, if one electron is detached from a sodium atom, the result is a positive sodium ion represented by Na^+. An atom that has lost more than one electron will have a greater positive charge, a condition indicated by placing a number before the plus sign. The number indicates the number of electrons that have been lost. For example, a calcium atom that has lost two electrons is represented by Ca^{2+}.

An atom can also acquire electrons. In this case it will no longer be a neutral sphere because it has acquired an additional negative charge. This type of ion is also indicated by the chemical symbol for the element, this time followed by a minus sign (−) indicating the number of electrons that have been acquired. A phosphorus atom with three additional electrons is therefore represented as P^{3-}.

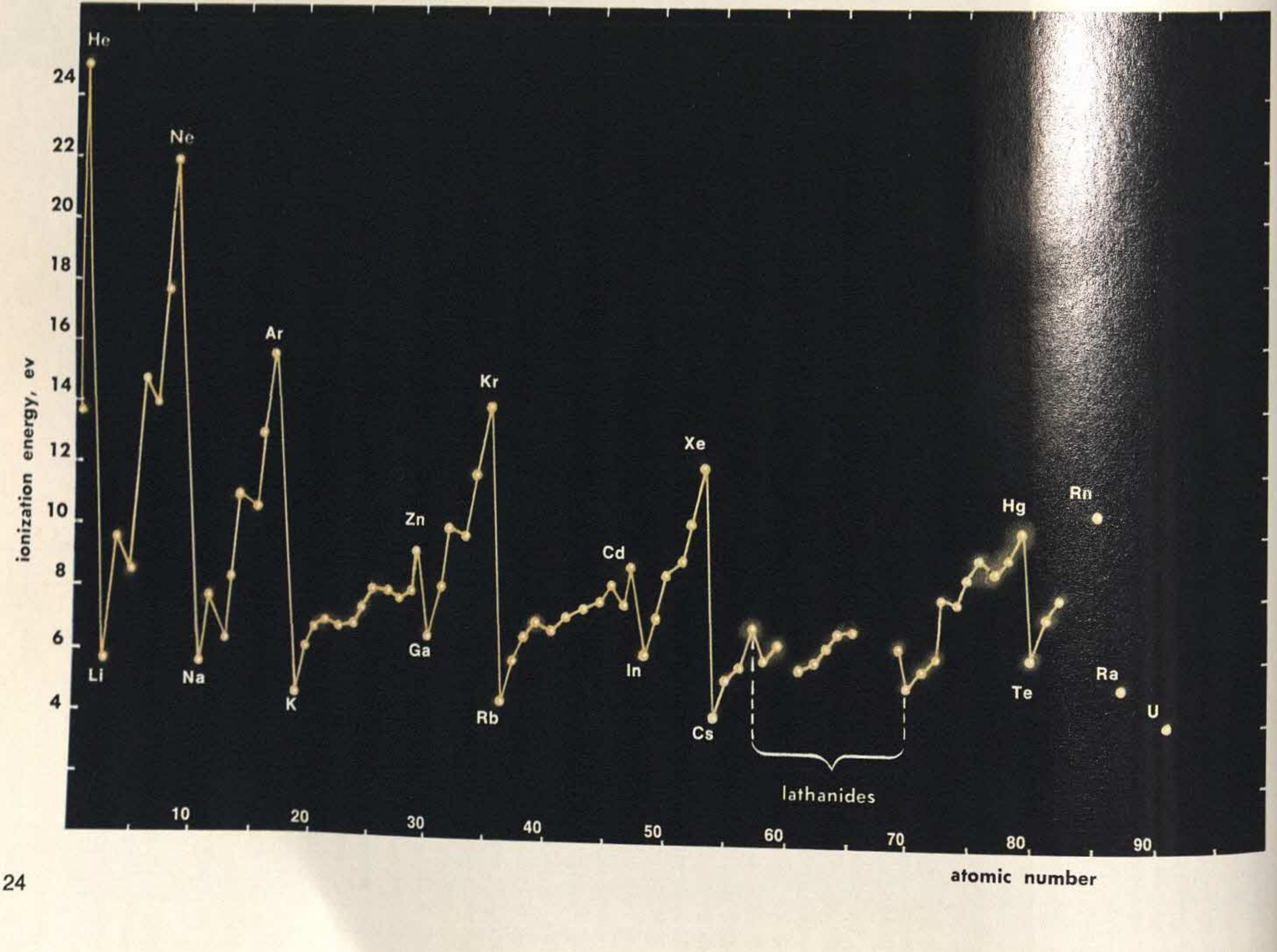
IONIZING POTENTIAL OF ATOMS

The ionizing potential of an atom—that is, the energy needed to detach an electron from the atom—is subject to periodicity. This can be illustrated by constructing a diagram similar to the one constructed for atomic volume, but in this case showing atom by atom how much energy must be expended to detach one electron. This will yield the curve in Illustration 4, which shows that ionizing potential rises and falls in a periodic manner.

The graph shows that the inert gases are the elements least prone to give up electrons, requiring the most work energy to detach one. All atoms of the inert gases have eight electrons in their outermost orbit, forming a stable structure.

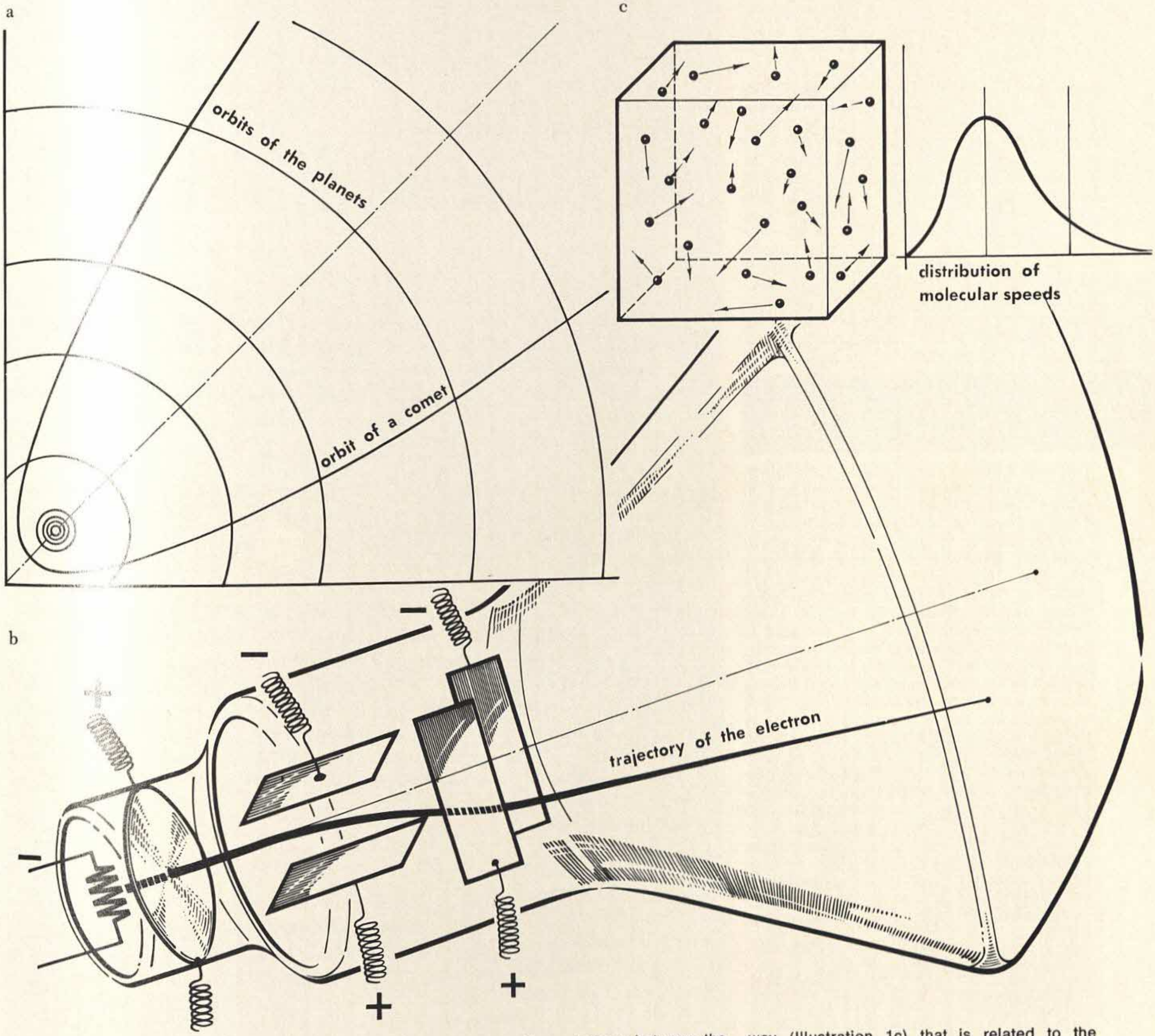
Conversely, the alkali metals have low ionization energies. A comparatively small amount of energy is sufficient to detach one of their peripheral electrons. (When an atom is ionized several times, the first electrons to be detached are the outermost ones, with detachment proceeding gradually inward toward the nucleus.)

4



ATOMIC THEORY AND CLASSICAL MECHANICS | the extension of Newton's laws

1

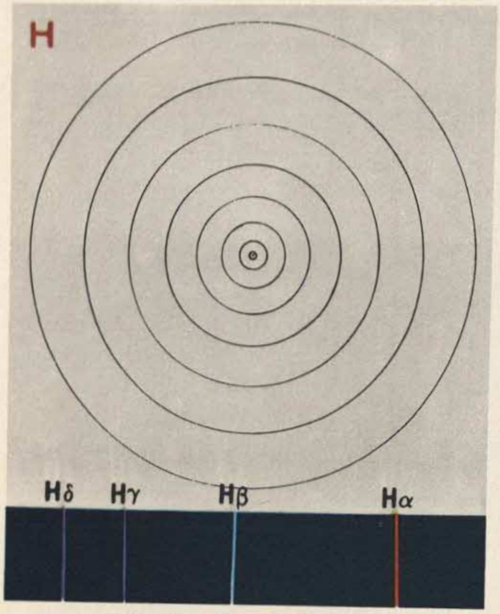


THE APPLICATION OF CLASSICAL MECHANICS—Illustration 1a shows the orbits of the planets. If a comet enters the solar system, and the forces of attraction that will be exerted on the comet by the planets and the sun are known, the course of the comet can be predicted accurately by applying the laws of classical mechanics.

The movement of an electron between the electrodes of a cathode-ray tube (Illustration 1b) is determined by classical mechanics, which provides an accurate prediction of the particle's trajectory, if the arrangement of the electrodes and intensity of the field are known.

The molecules of a gas collide with one another and change direction and velocity in a way (Illustration 1c) that is related to the collisions that take place. Classical mechanics can predict the distribution of the molecules in the gas. The accompanying graph shows the Maxwellian distribution of speeds for gas molecules.

2



THE INADEQUACY OF CLASSICAL MECHANICS—Classical mechanics is inadequate to explain many phenomena in atomic physics. Three examples of such phenomena follow:

Atoms isolated in space, as in a gas, can be excited to the level of energy at which they emit light. The visible radiations emitted are made up of well-defined colors; analysis shows that the spectrum of excited atoms (bottom of illustration) consists of several discrete lines. This behavior of excited atoms can be explained only if their electrons are considered as not being arranged around the nucleus in the way that the planets are arranged around the sun and as not being governed by the laws regulating the motion of the planets. The electrons must be considered as rotating around the nucleus only in orbits of certain shapes that are not predictable by classical mechanics. The top part of the illustration shows how the electrons of a hydrogen atom rotate around the nucleus according to the quantum theory, which predicts the arrangement of electrons inside an atom when there is a reasonable amount of potential and kinetic energy present.

Classical mechanics may be said to have begun with Sir Isaac Newton's formulation of his three laws of motion that establish that the motion of bodies is determined by forces and explain the effect of a known force acting on an object of known mass. Newton used these fundamental laws of mechanics to work out a mathematical system that can predict the motion of all material bodies.

The major achievements of classical, or Newtonian, mechanics were initially concerned with the motion of celestial bodies. The motion of a planet is determined by the attraction exerted on it by the sun and the other planets; however, if the attracting force exerted on a planet is very weak, its motion will be affected to a very small extent. Years and sometimes centuries of observation are required to detect the deviation of a celestial body from the motion it would have if the sun were the only force acting on it. Yet celestial mechanics, which was derived from the Newtonian system, allows astronomers to predict with mathematical accuracy even the deviations caused by the very weakest of disturbances.

Classical mechanics, at first applied to large mechanical systems with success, was later found to be adaptable to the description of the motion of microscopic bodies such as electrons and other atomic particles that freely move in space, or at least that are situated at much greater distances from each other than they are found to be in matter under normal conditions.

Phenomena exist, however, that Newton's laws cannot explain. Classical mechanics is insufficient to explain, for example, certain phenomena of atoms and the particles of which they are composed. Newton's laws are accurate for the world in which human beings are accustomed to live, and they are easy to understand intuitively through geometry.

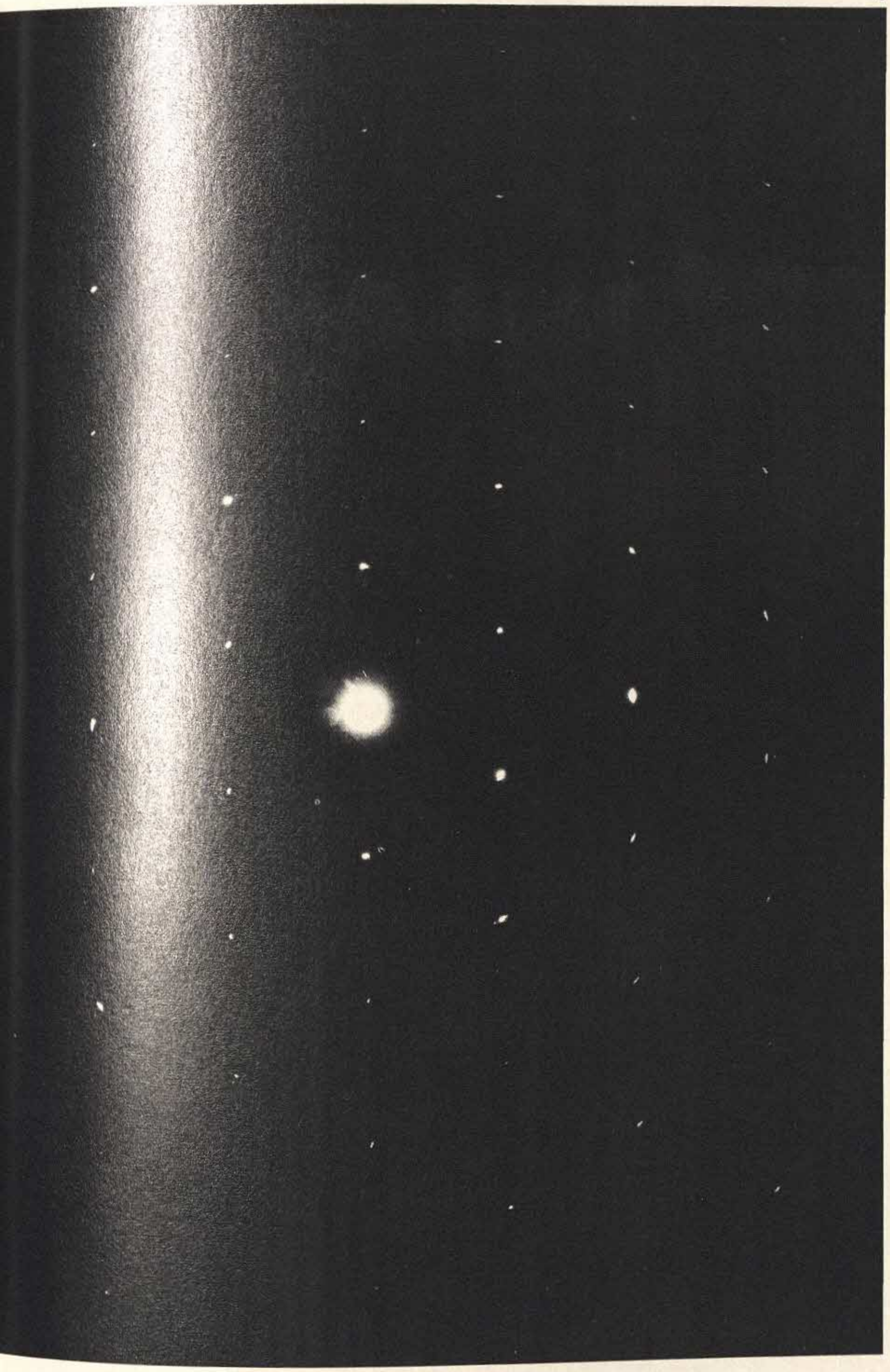
Einstein's special theory of relativity demonstrates that the laws of classical mechanics are not valid for bodies traveling at velocities approaching that of light; the motion of a proton inside an accelerator, for example, cannot be predicted by Newtonian mechanics. Another kind of mechanics has to be used in such cases—a relativity mechanics based on the knowledge supplied from electromagnetic radiations such as light. Relativity mechanics assumes that light takes a finite time to travel a certain distance, while classical mechanics presumed that light was propagated with absolutely no time lag.

The mechanics of bodies moving at velocities approaching the speed of light stem from the special theory of relativity, which does not actually contradict the laws of classical mechanics. If the formulas of the special theory of relativity are applied to bodies moving at a velocity that is very low compared to that of light, the formulas are found to coincide with those of classical mechanics, which means that relativity mechanics can be thought of as an extension of classical mechanics.

The need for a system more comprehensive than that of classical mechanics was demonstrated by several experiments carried out at the end of the nineteenth century. The subsequent study of atomic physics and of matter also emphasized the need to improve on classical mechanics with still another new system known as quantum mechanics.

The way electrons move around an atomic nucleus and the laws regulating collisions between subatomic particles and electromagnetic radiations are phenomena that can be interpreted and explained only by quantum mechanics, and this system of mechanics is applied generally to most atomic and subatomic phenomena. As the dimensions of the particles increase, quantum mechanics becomes identical with classical mechanics.

3

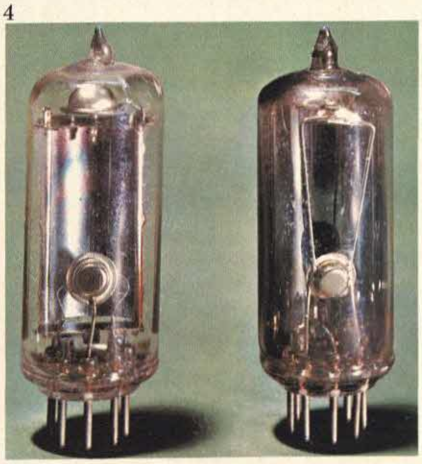


THE DIFFRACTION OF ELECTRONS—This photograph was obtained by recording the tracks of electrons that have passed through a crystal of mica. The electrons have been diffracted exactly as if the crystal had been traversed not by particles but by electromagnetic radiations such as x-rays. The same diffraction pattern can be obtained with x-rays, indicating that electrons in motion behave both like waves and like particles. Classical mechanics cannot explain why electrons exhibit this dual behavior.

THE PHOTOELECTRIC EFFECT—These photoelectric cells are used to measure the intensity of light by means of a phenomenon known as the photoelectric effect. Light falling on a metal surface extracts electrons from it. The metal surface is connected to a generator that replaces the lost electrons. The replacement electrons reach the metal surface through a wire, through which passes an electric current with an intensity proportional to that of the light that strikes the metal surface.

The photoelectric effect demonstrates the corpuscular, or particle, nature of light waves. To extract electrons from a metal surface, light radiation must have a wavelength less than a particular wavelength that depends on the nature of the metal. If the wavelength of light is greater than this particular wavelength, it will not extract the electrons, however intense the radiation may be. This phenomenon can be explained only if light radiation is considered as being made up of small packets, each possessing an amount of energy related to the wavelength of the radiation rather than to its intensity. The intensity of a radiation is expressed by the number of packets of energy that traverse the light ray in one second. These packets of energy are known as electromagnetic quanta, because they represent the smallest quantity of light energy that can be contained in a ray of light. This and certain other phenomena are not predictable by classical mechanics and suggested the need for a more comprehensive system of mechanics.

4



ELEMENTARY PARTICLES | photons, leptons, mesons, baryons

For more than 2,000 years the idea persisted that the atom was the smallest indivisible particle of matter. Not until the early nineteenth century were concepts of the atom and of atomic structure consolidated, making it possible to explain, for example, how chemical reactions took place. At this time, however, the concept of the atom was primitive and nebulous. No one knew quite what an atom really was; its structure was unknown, although it was presumed to be a very small quantity of an element.

X-ray and spectroscopic studies later made it possible to learn more about the atom and to construct certain hypotheses (later confirmed) regarding its constitution, the arrangement of its electrons, and its nucleus. Yet the picture of the atom took shape with only limited understanding of the structure of the nucleus.

Practically speaking, intensive nuclear research did not begin until the 1930s, when an entire series of new instruments was devised and a great deal of theoretical knowledge was developed. Despite the advancement in knowledge that has taken place in recent years, this research is far from complete. Because of its complexity, nuclear research is still an open field for research and experiment.

When the study of atomic structure began, the laws needed to describe the behavior of atomic particles were not yet known, even though the nature of atomic forces (primarily electromagnetic) was understood. The appropriate laws were subsequently formulated through the introduction of quantum mechanics.

In the case of the later study of the nucleus, physicists knew the mechanics to apply (quantum mechanics), but not the nature of the forces that keep the particles of the nucleus together. The nature of these forces is only partially known even today, and no completely satisfactory theory has yet been advanced. Once again, however, it has been possible to study the structure of atomic nuclei, at least in part, without a precise knowledge of the nature of the particles of which they are composed—the nucleons, protons, and neutrons.

Later, attention was concentrated on the study of subnuclear particles, and today this subject is one of the most important concerns in the whole of physics. The scientist's knowledge of subnuclear particles is still very imperfect. A complete picture of the properties of subnuclear particles and a valid theory will only become available when the forces the particles exercise on one another in all possible circumstances are understood, and this goal seems far away.

A VAST FAMILY

In nuclear physics the various nuclei are referred to in different ways. For example, a nucleus can be described as having an atomic number of 26; or, more simply, it can be called an iron nucleus because all nuclei with the atomic number 26 are atoms with the chemical properties of iron (quite a few isotopes exist). A discussion of particles, on the other hand, goes beyond the bounds of direct experience. To study the properties and behavior of particles, a physicist must first be able to detect them by using equipment capable of recording the traces they leave.

Detection of charged particles is based on the effects of the electromagnetic interactions of the particles with matter. As a result of such interaction, a particle loses a part of its kinetic energy and may come to a stop after having traveled a certain distance. Physicists also study the ways in which particles are deflected when they cross a magnetic field.

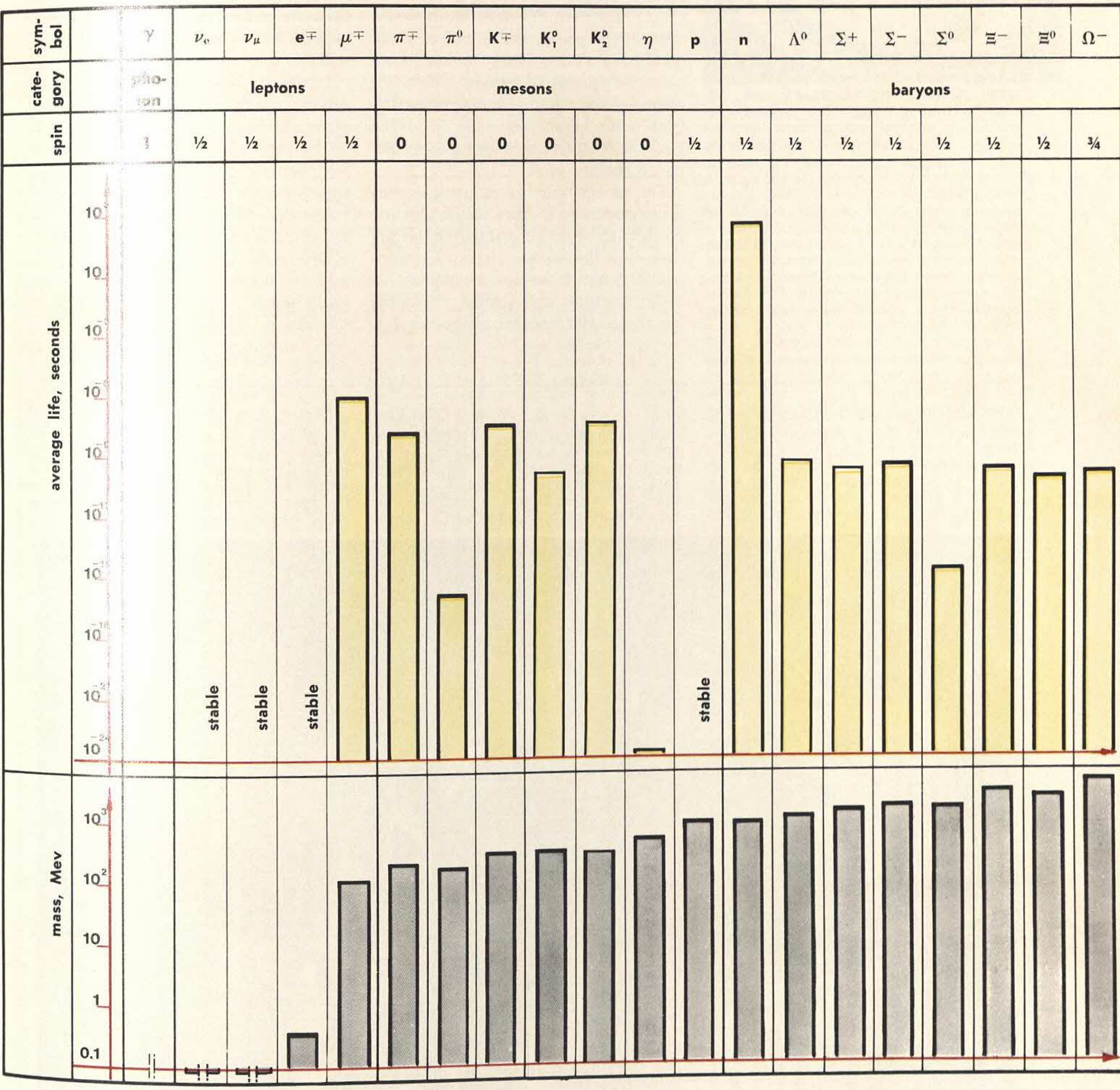
Research into elementary particles has indicated that every one of them has a counterpart with exactly symmetrical properties. These counterparts are now known as antiparticles. An example is the

THE PARTICLE FAMILY—In 1935 the Japanese physicist Hideki Yukawa predicted the existence of a particle having a mass intermediate between that of the electron and the proton. He gave it the name "meson," meaning a medium or intermediate particle. The actual discovery of the meson, however, came more than a decade after its prediction. Other particles with masses intermediate between the electron and proton, and some with masses greater than that of the proton, have since been discovered with increasing frequency. Physicists have also realized that many of the particles previously believed to be distinct were actually related.

Illustration 1 summarizes some properties of several subatomic particles. The particles are listed in ascending order of mass. The first, the photon, the quantum of electromagnetic radiation, has no mass; it is ranked among the particles because in many nuclear reactions it behaves as if it were a particle. The photon and neutrino particles have zero mass and travel at the speed of light. Apart from the photon and neutrino, the mass of a particle, as shown in the table, is its rest mass; that is, the mass of the particle when it has lost all velocity and has come to rest. Many particles do not survive long when at rest because they are unstable, in which case they must be observed while they are moving at a speed almost that of light. The mass of these particles then appears by relativity to be much greater than when at rest. Because many of the particles listed in the table are unstable and transform themselves into lighter particles in the course of their decay, it is convenient to measure their mass in terms of a unit that, when transformed into energy in accordance with the equation $E = mc^2$, corresponds to an energy of one Mev (one million electron volts).

In terms of this unit of mass, the electron has a mass of about 0.5, while the proton and neutron have a mass of about 1,000. The table divides the particles into light, medium, and heavy particles according to their mass. The light particles, or leptons, are those having masses of the same order of magnitude as electrons. They range from neutrinos, which in fact have zero mass, to mu-mesons, which have about 200 times the mass of electrons.

All other particles with masses intermediate between the mu-mesons and the proton are classed as medium-heavy particles, or mesons. The heavy particles, or baryons, have masses greater than the proton. A study of the table shows that once the particles have been arranged on the basis of their most important property—mass—they are also in a certain order as to their other properties. A case in point is spin, a property that is related to the rotation of the particle about its axis and that determines the number of orientations that a particle may assume with respect to a specified direction.


sym-bol
cate-gory
spin
γ
ν_e
ν_μ
$e^\mp$
$\mu^\mp$
$\pi^\mp$
π^0
$K^\mp$
K_1^0
K_2^0
η
p
n
Λ^0
Σ^+
Σ^-
Σ^0
Ξ^-
Ξ^0
Ω^-
pho-ton
leptons
mesons
baryons
1
½
½
½
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0
0
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½
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½
½
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½
½
½
¾
average life, seconds
10
10
10
10
10
10
10
10^{-18}
10^{-21}
10^{-24}
stable
stable
stable
stable
mass, Mev
10^3
10^2
10
1
0.1

2

HOW ELEMENTARY PARTICLES ARE DETECTED AND STUDIED—The properties of elementary particles are generally revealed by analysis of photographs of the tracks the particles have left in an instrument such as a bubble chamber. In general, the photographs enable scientists to ascertain the dynamic characteristics of the reaction phenomenon that has generated the particle or has led the particle to react with others. Before the bubble chamber became available, the work of discovering the particles and analyzing their properties was carried out by means of the Wilson cloud chamber, special photographic plates, and scintillation counters.

positive electron, or positron, which has the same mass as an electron, but an opposite charge.

Although no all-embracing system of particle classification has yet been devised, the system shown in Illustration 1 lists the properties of several of these particles in a fairly systematic way. Photons (the quanta of gamma radiation), electrons, and neutrons are particles that have been known for some time—the electron, for example, since the late nineteenth century.

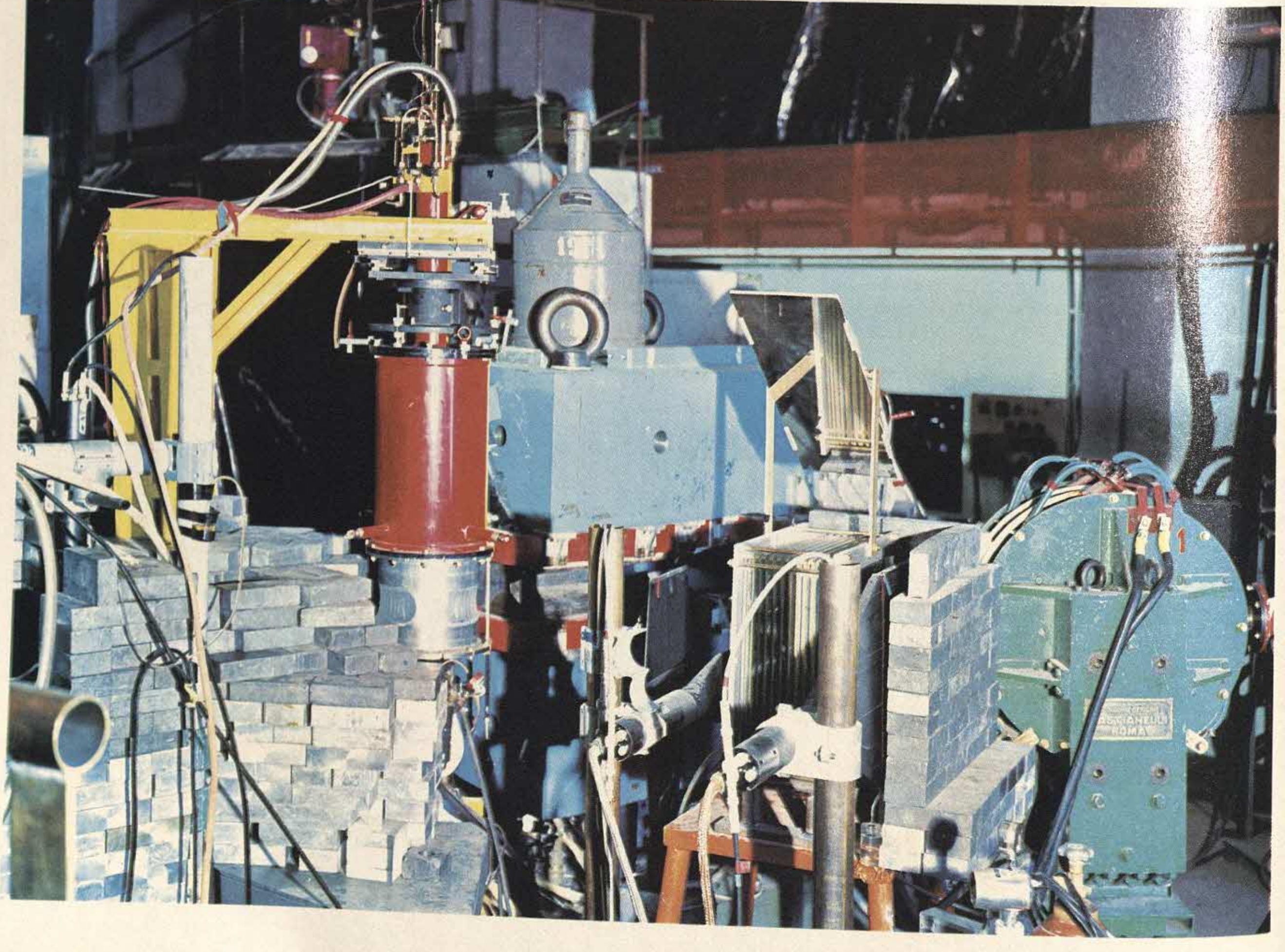
The greater number of particles was discovered after World War II. The first particles to be discovered during this period were the mesons; from the standpoint of mass, these are intermediate between electrons and protons (a proton has about 2,000 times the mass of an electron). Later still came the discovery of particles with masses greater than that of the proton.

Not all particles are stable. The electron, proton, gamma quantum, and neutrino are stable; but others, such as the neutron and many types of mesons, are unstable and decay into other particles.

In the late 1960s, scientists at the University of Utah reported the detection of an anomaly in the intensity distribution of very high energy cosmic ray muons (or mu-mesons, which have a mass approximately 200 times that of the electron). Interest in this branch of elementary-particle research rose sharply, stimulated by the possibility of discovery of a long-sought particle, "the intermediate vector meson," which mediates the weak interactions of elementary particles.

3

HOW PARTICLES ARE PRODUCED—In the early days of the study of elementary particles, cosmic radiation was the principal source of such particles. Cosmic rays contain particles having very high energies (protons, for example). The collision of these particles with atomic nuclei in the atmosphere, or with elements present in the detection equipment, gives rise to new particles. To produce these particles requires collisions involving an energy many times greater than the equivalent mass of the particles. To produce a particle having a mass equivalent to 1,200 Mev, the nucleus must be bombarded with a particle that has at least the same amount of energy. The illustration shows typical apparatus used in such an experiment, in which the bombarding particles are accelerated by means of a synchrotron. The apparatus used for detecting the particles produced is hidden behind a heavy shielding of stacked lead bricks.



THE ELECTRON | the elementary charge

Many concepts live on long after those who gave them birth. Five centuries before Christ, the Greek philosophers Leucippus and Democritus concluded that all the world was composed of atoms—minute particles of matter that were indivisible. The concept that the atom was the smallest quantity of matter persisted.

In 1897, the English physicist, J. J. Thomson, proved the existence of an even smaller particle, the electron, now known to be responsible for electrostatic and most electromagnetic phenomena. (When an electrostatically charged body is attracted by another body, the attraction occurs between the negative electrons present on one body and the positive charges of the electron-deprived atoms of the other.) Thomson had discovered the elementary charge, the smallest indivisible form in which an electric charge could exist. Scientists then turned to the problem of determining the magnitude of this electric charge.

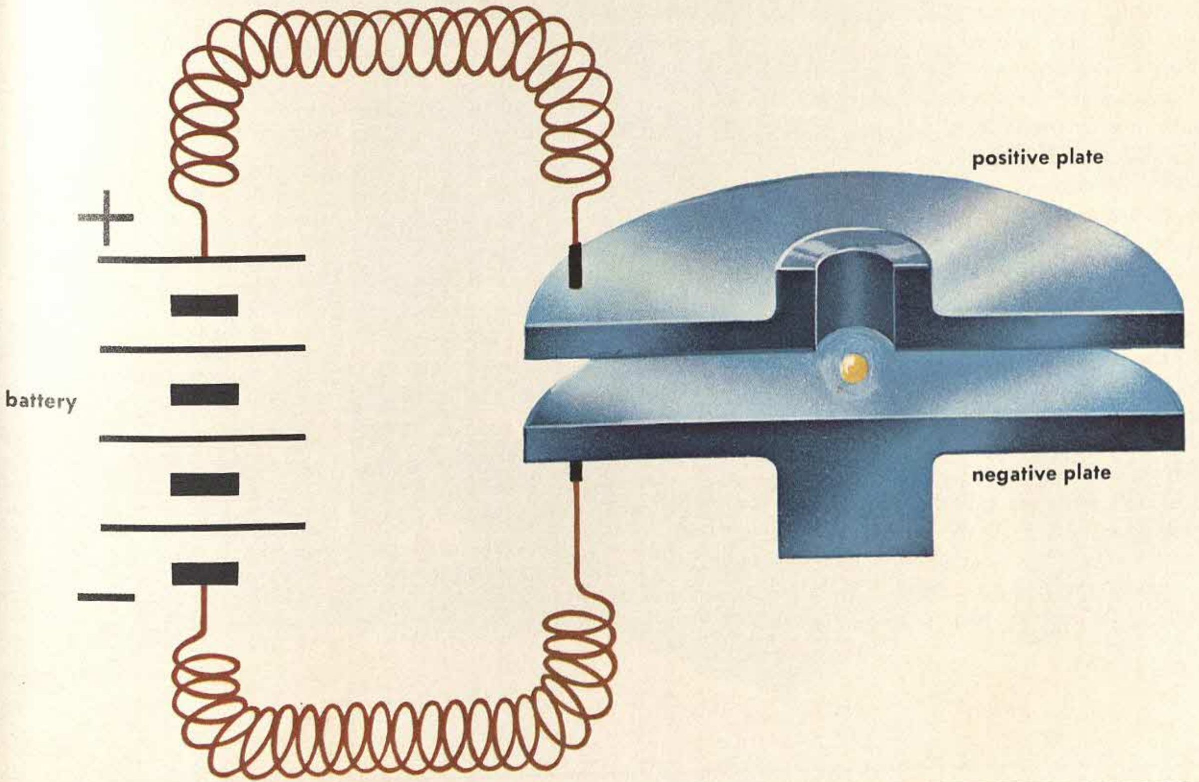
1

MEASURING THE CHARGE OF THE ELECTRON—A tiny droplet of liquid about the size of a dust particle is allowed to fall through air or other gas. If the air or gas is still, the droplet will fall slowly. The speed with which it falls depends on its density and mass, and on the resistance of the air. The droplet will fall at a constant speed. Although bodies in a vacuum fall at a uniformly accelerated rate, they will travel with a uniform terminal speed through a braking medium such as a gas.

In the diagram a liquid droplet is shown in the space between two metal plates connected to the poles of a battery. The upper plate is connected to the positive pole, the lower plate to the negative pole. If the droplet is given a negative charge, it will be attracted upward, toward the positive plate. The force of this attraction depends on the magnitude of the charge given to the droplet. Given a charge of appropriate strength, the droplet will remain suspended in air because its weight is perfectly balanced by the electrical force of attraction that tends to lift it upward.

The droplets of liquid must be very small, but they can be observed readily through a microscope. X-rays can be used to change the charge of the droplets by producing ions between the plates. The ions vary the charge as they collide with the droplets, and the droplets change speed. The speeds the droplets assume have certain well-defined values, and each speed corresponds to an equally well-defined increase of charge. The increases in the charge of the droplets are either equal to or multiples of a certain minimum quantity: the charge of the electron.

To calculate the value of the electron charge it is necessary to know the speed with which the droplets would fall if they were not charged. This speed can be calculated if the mass and radius of the droplet and the viscosity of the surrounding air or other gas are known. If the particle is charged, its speed of fall depends not only on the mass, radius, and viscosity factors, but on the intensity of the electrical field that the experimenter sets up between the two plates. The experiment is particularly fascinating when the charged droplet remains suspended between the two plates. This means that the force of the electrostatic attraction, which depends on the charge of the droplet and the intensity of the electric field, exactly counterbalances the weight of the droplet, which depends on the mass and dimensions of the droplet. To arrest a droplet of known dimensions, the experimenter varies the intensity of the electric field until it attains the required value. In this way the unknown charge can be determined. It is found that the charge of the droplets is always a multiple of 4.802×10^{-10} electrostatic units (esu).



Because electric charges attract or repel each other according to whether the charges are positive or negative, it is enough to follow conventional methods of mechanics in establishing a unit of measure for such charges. The unit of measure can be defined as that charge that, when placed at a given distance from another equal charge, will exercise a given force on the other charge. Using the centimeter, gram, and second as fundamental mechanical measuring units, the unit charge is one that exercises a force of one dyne on an equal charge one centimeter away from it—the so-called electrostatic unit (esu).

The next step is to determine how many electrons are necessary to form an electric charge of the same magnitude as the charge represented by 1 esu, or what fraction of 1 esu corresponds to the charge of an electron.

THE CHARGE OF THE ELECTRON

Knowing the magnitude of the electron charge opens the road to a wide range of other knowledge. Once the charges of the electrons and the atomic nucleus are known, for example, the force with which they attract each other can be determined through physical experiments showing the speed with which the electron revolves around the nucleus. The force with which ions tend to recapture the electrons they have lost, as well as the strength of the valency bonds that keep the atoms united in the various molecules, can also be determined. Furthermore, knowing the value of the charge of the electron enables physicists to determine the value of the mass of the electron. Experiments carried out to determine the mass of the electron do not arrive directly at the mass, but yield the value of the charge/mass ratio with great accuracy. To find the two parts of this ratio requires determining at least one of them by direct experiment. Once the charge is known, the value of the mass can be determined.

Knowledge of the electron charge also enables scientists to use electrolysis to determine Avogadro's constant, the number of atoms contained in one gram molecule of a substance.

The charge of other elementary particles such as protons and particles of cosmic radiation is equal to the electron charge (although it may have a different sign), making the electron charge a very important universal constant—a constant that must be known to determine other important constants. For this reason the measurement of the charge of the electron is of considerable importance to the entire field of physics.

HOW THE CHARGE OF THE ELECTRON IS MEASURED

The physicist has many methods by which he can measure the charge of the electron. Some of these methods are indirect. For example, if Avogadro's constant is known and the electric charge carried by a number of atoms equal to Avogadro's constant when each atom has a charge equal to that of the electron is known, the charge of a single electron can be determined by means of simple division. Many methods exist for determining Avogadro's constant; the second factor, the electrochemical equivalent, or Faraday, can be measured by means of electrolytic experiments. However, physicists are not satisfied with such indirect measurement. Whenever possible, they seek a direct means of measuring the quantities that interest them.

From 1908 to 1910, the American physicist Robert A. Millikan sought a direct method and succeeded in measuring the charge of the electrons by means of what is now known as the oil-drop experiment.

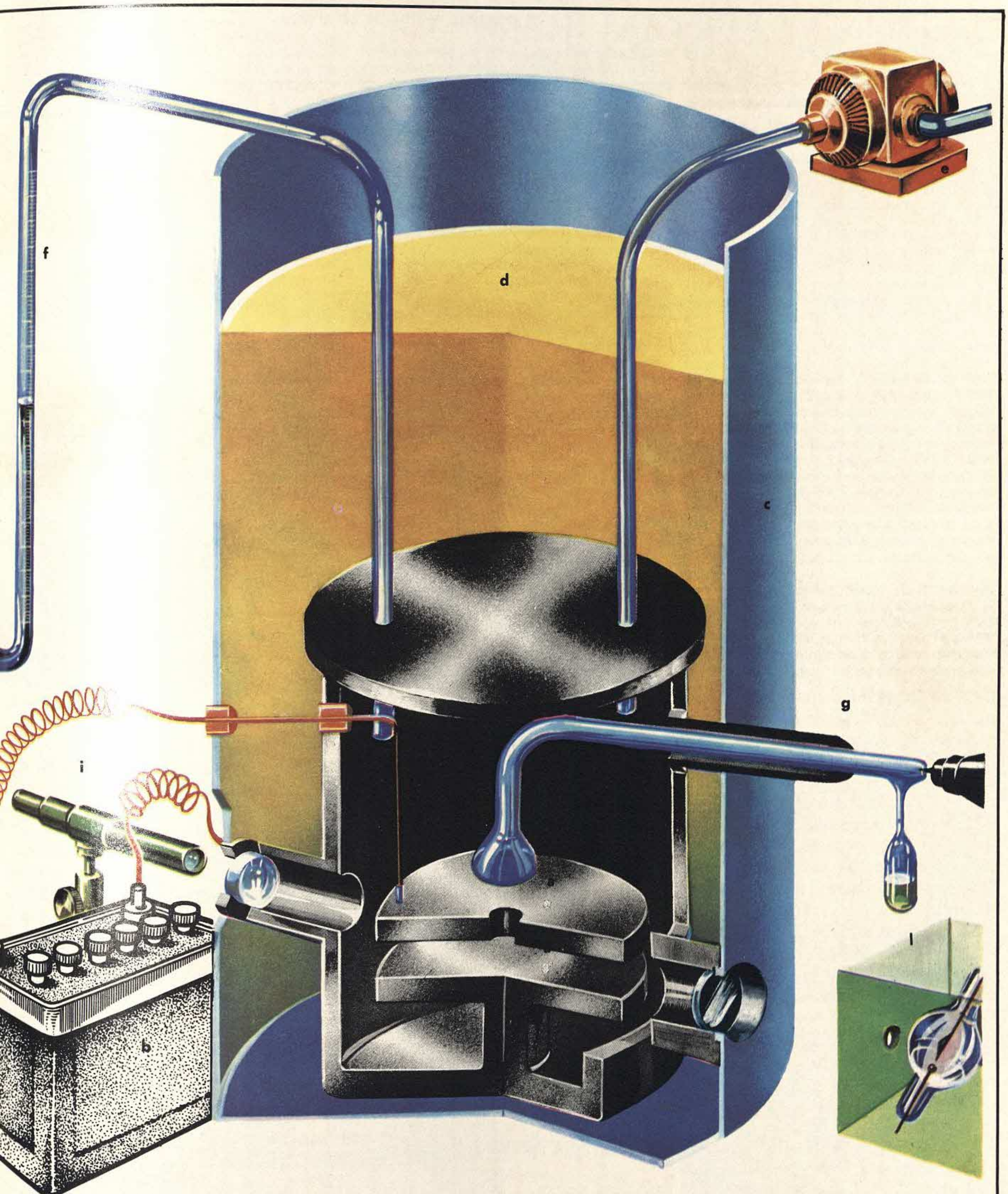
2

THE OIL-DROP EXPERIMENT—The equipment needed for the oil-drop experiment is shown in somewhat simplified form. The two plates **a** and **a′** are electrically charged and serve to control the falling motion of charged drops. A battery **b** produces an electric field between **a** and **a′**. One of the two poles of the battery is grounded, as in the lower plate **a′**. The other pole is connected to the upper plate **a**. The experiment is carried out inside a container **c**. The gas within this container must be perfectly still, for if it moves it will blow the oil droplets away from the field of observation. The temperature of the container must be kept constant over the whole of its surface; this is done by immersing the container in a liquid bath **d** whose temperature is kept constant by means of a thermostat (not shown). Since the liquid droplets will fall more rapidly if the gas is rarefied, a pump **e** reduces the gas pressure inside the measuring container. A variation in the electric charge of a drop of oil has a considerable effect on its velocity, and this can be clearly seen. The speed of uncharged falling particles depends on the density of the air or gas, becoming greater as the pressure decreases. This pressure must be known exactly and is measured by a gauge **f**.

The oil droplets are produced through a spray nozzle **g** of the kind generally used for aerosols. The liquid should not be volatile because evaporation would change the diameter of the drops during the experiment.

A source of light (not shown) illuminates the drops that enter the measuring container and ensures their visibility. The drops that pass through an opening in plate a are observed as they fall between the plates by means of a microscope **i** placed outside the observation chamber. The magnifying power of the microscope need not be great, but the instrument must be so constructed that it can measure the speed of the drops crossing its field of view. For this purpose, the eyepiece of the microscope contains a graduated scale. The light illuminating the droplets must come from a right angle to the axis of the microscope so that the drops will stand out clearly against a dark background. Normally, the droplets produced by the nozzle are already charged; in fact, they acquire their charge in rubbing against the walls of the nozzle as they come from the atomizer. X-rays are used to vary the charge. These x-rays are produced by a tube **l**, which is screened to protect the observer from potentially dangerous radiation. The x-rays enter the observation chamber through an opening that does not absorb them—for example, an opening in a thin sheet of aluminum foil.

Despite the precautions cited to ensure accurate measurement of the electron charge, the success of the experiment depends to a great extent on the skill of the observer.


f
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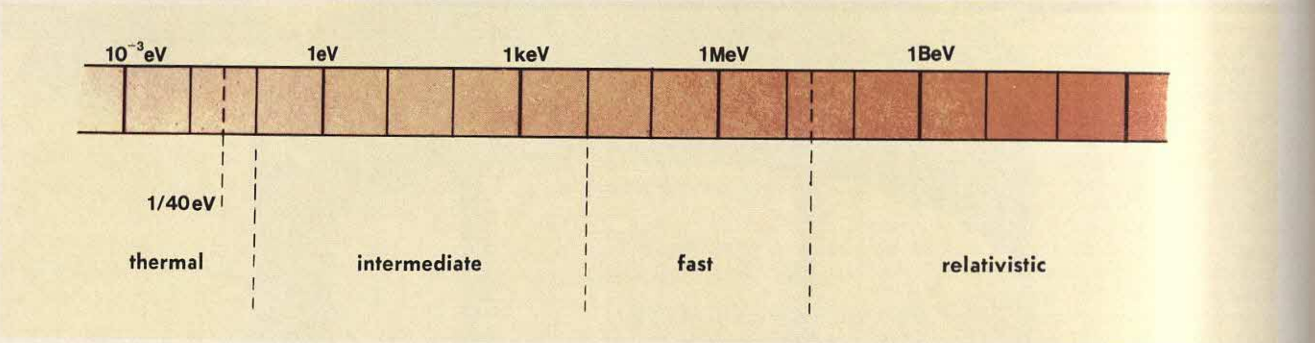
THE NEUTRON | a particle without charge

1



THE WIDE ENERGY RANGE OF THE NEUTRON—This scale of energies shows the extent of the neutron's energy range and its principal subdivisions. The region of least energy—extending from about 1/1000 ev to about 1/10 ev—is that of thermal neutrons. In this region neutrons place themselves in thermal equilibrium with the molecules of gases or solids, just as if they themselves were molecules or corpuscles suspended in Brownian motion. Such neutrons do not all have the same energy. Distribution of energies among the neutrons corresponds to a Maxwell type of velocity distribution among the molecules. It is more convenient, however, to consider thermal neutrons as having energies of about 1/40 ev each, or, more precisely, energies of the most probable value suggested by the distribution law—0.0253 ev.

The second field of neutron energies—extending from 1/10 ev to 10 kev—is that of intermediate neutrons. Depending on their energy levels, neutrons in this field have a high or low probability of being captured by the nuclei. Possibility of absorption is thus determined by resonance values.

The field of fast neutrons extends from about 10 kev to 15-20 Mev. In this range the reactions change with varying neutron energy.

The field of relativistic neutrons is often difficult to distinguish from that of fast neutrons, because of the gradual appearance of relativistic phenomena.

The neutron is a particle that has no electric charge, and that has a mass similar to that of the proton. Discovery of this elementary particle was made less than forty years ago, although the British physicist Ernest Rutherford predicted its existence in 1920. While Rutherford did not learn the characteristics of the neutron, his studies indicated that the presence of such a particle contributes to the mass but not to the charge of the nucleus, and it was he who gave the neutron its name.

In 1930 two German physicists, W. Bothe and H. Becker, discovered that when the metal beryllium was struck by alpha particles, a highly penetrating radiation was emitted, which they assumed to consist of gamma rays. Two years later the French physicist Frédéric Joliot-Curie and his wife Irène made an important discovery while examining the absorption of these rays. When paraffin or any other hydrogen-rich material was placed in the path of the unknown rays from beryllium, high-energy protons were ejected from the paraffin. They assumed the gamma rays were releasing these protons.

Not satisfied with this explanation, James Chadwick, an associate of Rutherford's at the Cavendish Laboratory at Cambridge, performed experiments of his own that indicated that an electrically neutral particle, rather than the gamma rays, was responsible for the radiation. Physicists subsequently learned to produce this new particle—the neutron—in different ways. They used it as a projectile for bringing about nuclear reactions; and suitable detectors were constructed for signaling its passage across matter and studying the effect.

Scientists further discovered that the neutron brought about the fission of uranium, and that it was more effective in provoking certain nuclear reactions when it had a small rather than a high energy level, as was first suspected.

In 1934 Enrico Fermi and his collaborators showed that nearly every element in the periodic table may undergo a nuclear transformation when bombarded by neutrons. In many cases, radioactive isotopes are formed in this way.

PROPERTIES OF THE NEUTRON

Neutrons make up a considerable portion of the mass of an atom. The value of the neutron's mass is 1.67247×10^{-24} grams. This mass is greater than the sum of the mass of a proton and an electron. Thus an exoenergetic reaction occurs if a neutron is split between these two particles.

When isolated from the atoms and particles, the neutron is unstable, behaving like a radioactive particle. In a free state it disintegrates into a proton, a negative electron, and a neutrino, liberating an energy of 0.786 Mev. The neutron is able to remain free for a long time, and has the ability to stay in thermal equilibrium with matter.

The spin of the neutron is 1/2, and its magnetic moment is equal to −1.9135 nuclear magnetons.

Having no charge, the neutron is able to approach and react to nuclei with greater ease than other particles. It is thus highly useful in bringing about nuclear reactions. The only forces to which the neutron becomes subject are nuclear ones at a short distance from the nucleus.

Neutrons cannot be accelerated—they must be accepted with whatever energy they have upon formation—but they can be retarded by permitting the neutrons to collide with nuclei; in each collision some energy is lost.

SOURCES OF NEUTRONS—Neutrons found in nature are barely active. A few neutrons are present in radiation that has traversed the atmosphere and created nuclear reactions with the nuclei of atmospheric gases. However, such neutrons cannot be used for research purposes. Consequently, a large number of artificial sources has been developed.

The most economical and simple sources of neutrons are radium-beryllium (Illustration 2a) or polonium-beryllium (Illustration 2a′). Both elements produce neutrons by nuclear reaction:

$$^{9}\mathrm{Be}(\alpha,n)^{12}\mathrm{C}.$$

The alpha particle is emitted by radium or by polonium, which is a naturally radioactive element like radium. The radioactive element is mixed with beryllium, and the two are placed in a hermetically sealed metal container. Neutrons produced in this manner have energies varying from 1 to 10 Mev.

Other sources of neutrons are those of the photoneutronic type. These, too, are economical, and of a small physical size. They utilize elements that emit neutrons after being struck by a gamma ray. The gamma ray reacts with a radioisotope mixed with beryllium or some compound having a high deuterium content—that is, a compound whose molecule contains a high percentage of deuterium in place of the normal hydrogen. The reaction will then be either

$$^{9}\mathrm{Be}(\gamma,n)^{8}\mathrm{Be}$$

or

$$^{2}\mathrm{H}(\gamma,n)^{1}\mathrm{H}.$$

These sources are almost monoenergetic, supplying neutrons whose energies are very close to each other and narrowly dispersed. Energy of the neutrons ranges between about 0.1 Mev and 0.6 Mev.

A source of high-energy, relativistic neutrons is obtained by using an accelerator of high-energy particles as the source of gamma radiation. A large accelerator of electrons or protons, for example, can produce gamma rays with an energy between 0.5 and 20 Bev. (One Bev corresponds to 1 billion ev.) These gamma rays produce photoneutrons of the required energy in the beryllium or the deuterium.

Fast neutrons can be obtained from reactions produced by particles accelerated in a Van de Graaff machine or by the Cockroft and Walton apparatus. Such equipment makes it possible to obtain beams of particles having a well-defined energy; the beams are then brought to bear on targets, permitting the particles themselves to produce neutrons. Neutrons from this reaction have a well-defined energy for every angle of emission. With a single type of reaction it is thus possible to produce neutrons with energies ranging from a minimum to a maximum value.

Illustration 2b shows a reaction chamber for the production of particles. The chamber receives the beam, directs it onto the target, and collects the neutrons produced.

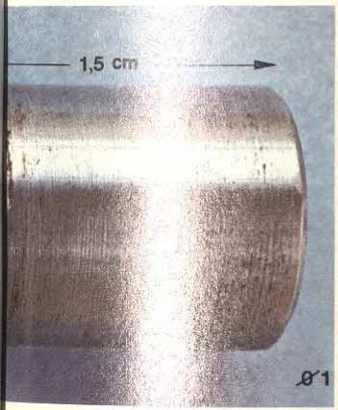
Illustration 2c shows a speed selector for slow neutrons.

All the sources described are of relatively low intensity. In the case of polonium-beryllium or photoneutronic sources, intensity depends on the intensity of the source emitting alpha or gamma particles, and may reach a few curies. When the primary source consists of particles coming from an accelerator, the beam emerging from the accelerator rarely attains an intensity of one milliampere. In the case of thermal neutrons, however, high intensities can be obtained by a reactor. In the core of a reactor are neutrons that have just come out of the uranium fission reaction, and have energies of about I Mev. Together with these neutrons are other neutrons whose energies have been lowered because they have been slowed down by the moderator.

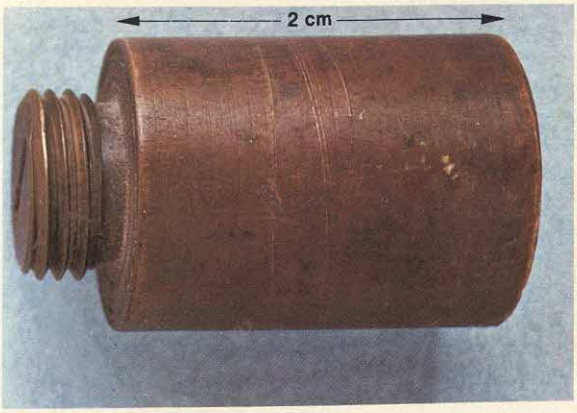
There is thus an extensive range of neutron energies. However, if a block of moderating material, called a thermal column (Illustration 2d), is inserted in the reactor, the neutrons will penetrate it and become diffused over its volume. A large energy spectrum will collect at the entering point; at the opposite end the neutrons will all be thermal. A cavity can be introduced into the thermal column in which materials are placed for irradiation by the neutrons.

To obtain the energy spectrum of neutrons produced by fission, a thin foil of fissile material—uranium-235, for example—is placed against the end of the thermal column. The neutrons produced in this manner are not slowed down, and give the characteristic fission spectrum.

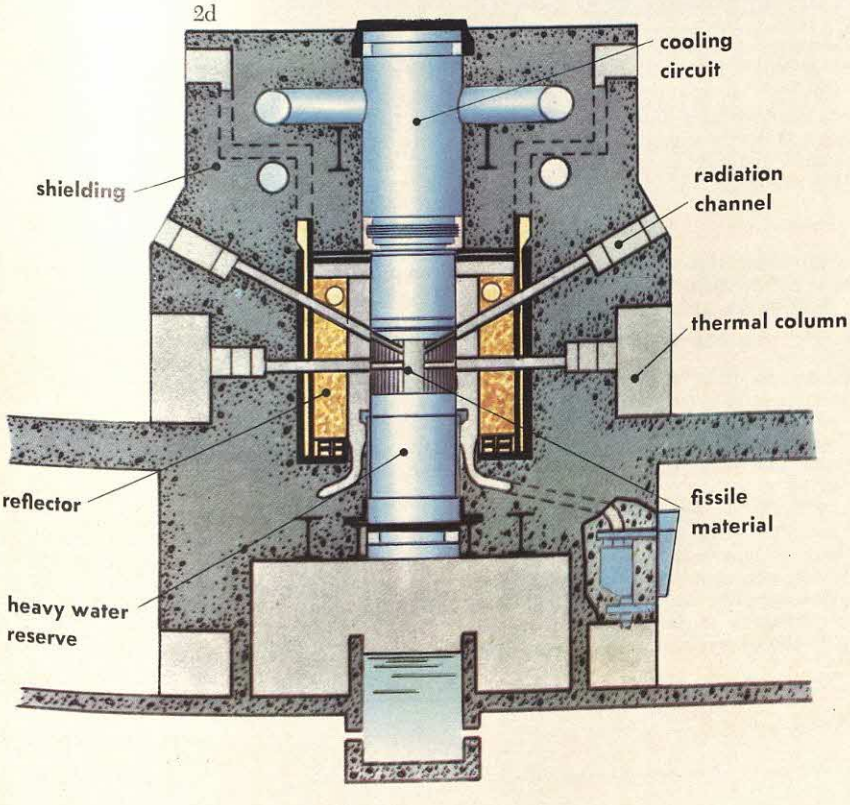
2a



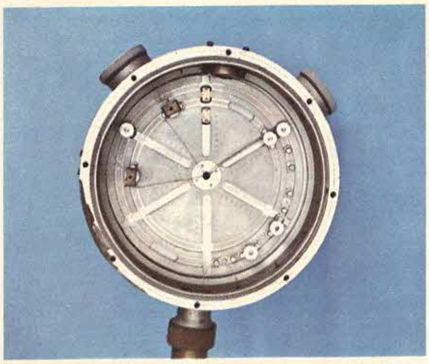
2a′



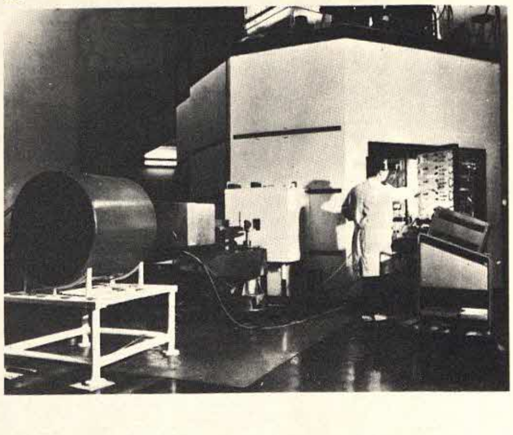
2d



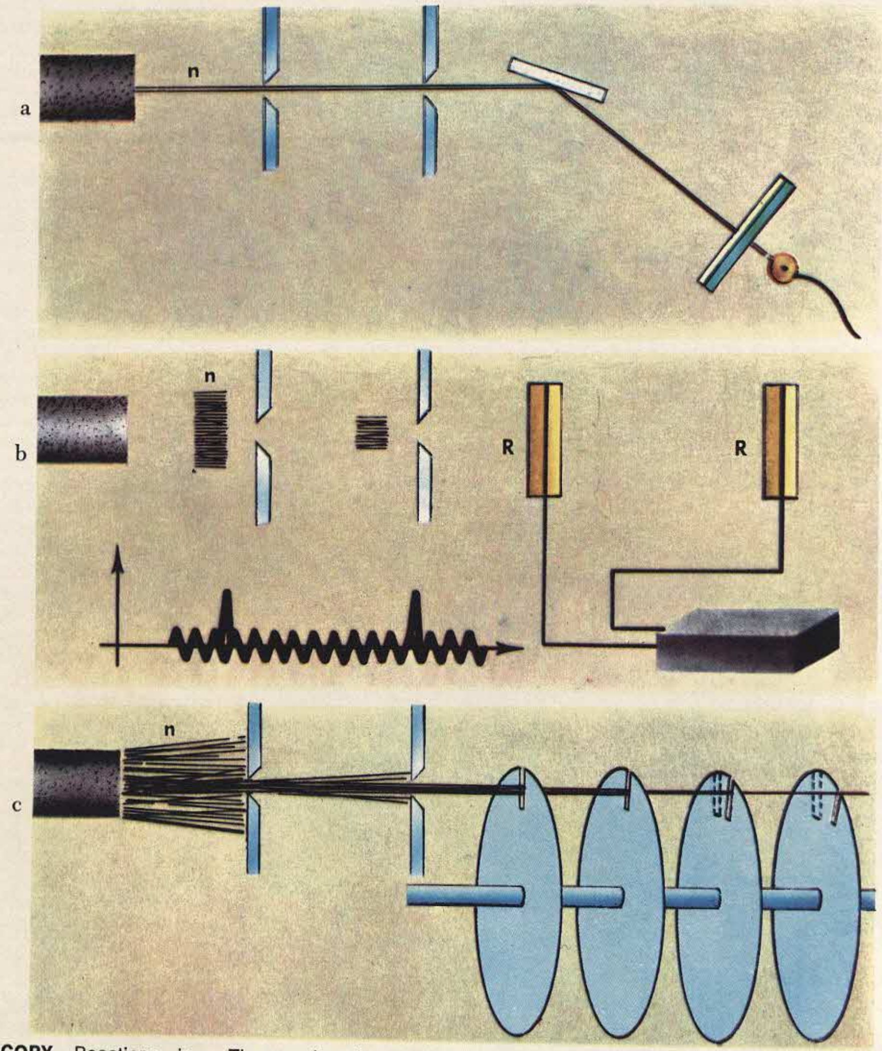
2b



2c



3



NEUTRON SPECTROSCOPY—Reactions induced by fast and relativistic neutrons and the probability of their occurrence are only slightly affected by the energy of the incident particle. Neutrons with intermediate energies. however, behave differently. Some neutrons produce no reaction; other neutrons with a slightly greater energy—even one part per thousand greater—will produce extensive reaction. To study reactivity properties of the nuclei in relationship to the absorption of neutrons, it is necessary to have beams of particles whose energy is known. This is accomplished by using a source that produces neutrons with all the energies of the range, and then choosing from among them those with a particular energy.

With intermediate neutrons, the amount of energy depends on the speed, which may vary from a few to many kilometers per second.

One method of selecting neutrons with a particular speed from a beam that contains neutrons with varying energies is by causing the beam to be reflected by a Bragg crystal (Illustration 3a). Neutrons **n** in motion behave in accordance with the quantum theory: they are associated with a wave, just as are electrons that are used in the electron microscope. The wavelength λ of neutrons is given in terms of their speed by the formula

$$\lambda = h/Mv,$$

in which h is Planck's constant, M the mass of the neutron, and v its speed. In terms of energy, the formula is

$$\lambda = h/\sqrt{2ME},$$

in which E is energy. Introducing numerical values of the constants, and expressing E in electron volts, the formula becomes

$$\lambda = 2.86 \times 10^{-9} \sqrt{E}$$

and the wavelength is given in centimeters.

With thermal neutrons, the energy is about 1/40 ev and the wavelength 10^{-8} cm, that is, one Ångstrom, as in the case of x-rays used to determine the structure of crystalline substances.

For $E = 100$ Mev the wavelength is about 10^{-13} cm. The wavelength thus passes from the range of atomic dimensions to those of subnuclear ones, approaching dimensions such as those separating nucleons in the nucleus. Bragg reflections at different angles are obtained through these variations in wavelength by the following method: the beam of neutrons is collimated and made to strike a crystal in which the nuclei diffuse the neutrons; the neutrons then scatter at different angles according to their energies.

A second method of determining the speed of neutrons **n** is by producing a brief emission of these particles and measuring the time spent to cover a known distance, generally 10 or 20 m (about 33 or 66 ft). A source of neutron impulses is created by a target struck by particles producing neutrons. In Illustration 3b, two detectors **R** measure traveling time. Neutrons with an energy of 1 ev take 723 microseconds to cover 10 m; at an energy of 1 kev, such neutrons take 22.9 microseconds to travel 10 m.

The method most frequently used is that of the rapid selector (Illustration 3c). Molecules of a particular speed are selected from a gas in order to study speed distribution. Metal disks, in which holes have been cut to allow neutrons **n** to pass, are mounted on a shaft. The relative displacement of these holes and the speed of rotation define the speed of the neutrons that will pass through the selector.

RADIOACTIVE DISINTEGRATION

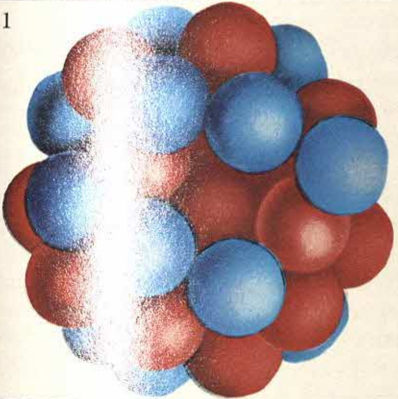
energy emitted by atomic nuclei

Radioactive disintegration is a phenomenon involving the emission of particles or radiation from atomic nuclei. In order to understand the reasons for these emissions, it is necessary to understand the composition of the nuclei and how the nuclei are changed by these emissions.

ATOMIC NUCLEI

Atomic nuclei contain virtually the entire mass of an atom and are essentially composed of two kinds of particles, protons and neutrons. Protons and neutrons have almost identical masses, but protons have a positive electrical charge, whereas neutrons have no electrical charge. Every nucleus, therefore, has a total charge equal to the sum of the charges of its protons. Because every proton has the same charge, the total charge of a given atomic nucleus equals that charge multiplied by the number of protons in the nucleus.

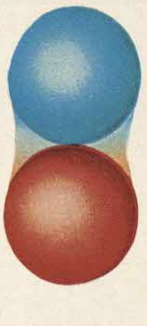
1



THE CORE OF THE ATOM—At the center of the atom is the nucleus, composed of neutrons and protons.

The charge of the nucleus, in turn, determines its capacity to hold in orbit around it the electrons that, together with the nucleus, comprise the atom—forming a kind of miniature solar system. The chemical properties of the atom are determined by the number and arrangement of the electrons; and these chemical properties are identified by the name of the element itself. Because the number of electrons (which determines the properties of the element) is equal to the number of protons in the nucleus, it follows that this number—the atomic number of the element—serves to define the properties of the element.

2

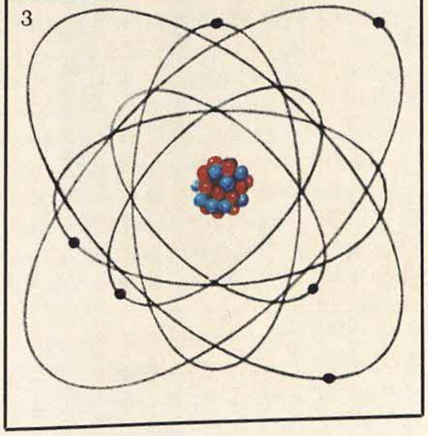


THE FORCE THAT FORMS THE NUCLEI—When a neutron (blue) is brought close to a proton (red), an attractive force results that makes possible the formation and existence of the nucleus.

So far both protons and neutrons have been described as material particles, the former with a positive charge, the latter neutral. Actually, both are entities with somewhat complex structures. The positively charged protons, when grouped together in a nucleus, would have a tendency to repel each other and move away from each other. Nuclei containing a large number of protons, however, also contain a large number of neutrons; their presence helps hold the protons together. The actual cohesion of the nucleus is the result of nuclear forces—"exchange forces"—that are exercised without distinction between all nucleons (protons and neutrons). If a proton is brought close to a neutron, a force of attraction is exercised that unites the two particles.

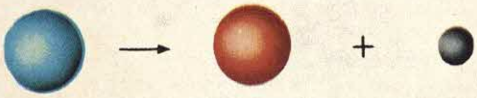
THE ATOM—The chemical properties of the atom depend on the number and arrangement of the electrons that orbit the nucleus.

3



Every nucleus except that of hydrogen (which consists of a single proton) consists of a certain number of protons and an equal or greater number of neutrons. The neutrons, which would disintegrate to half their number in about 13 minutes if detached from the nucleus, are stabilized because of their bond with the protons. Without that bond, a neutron changes into a proton and an electron. This and other phenomena are related to the subject of radioactive decay.

4

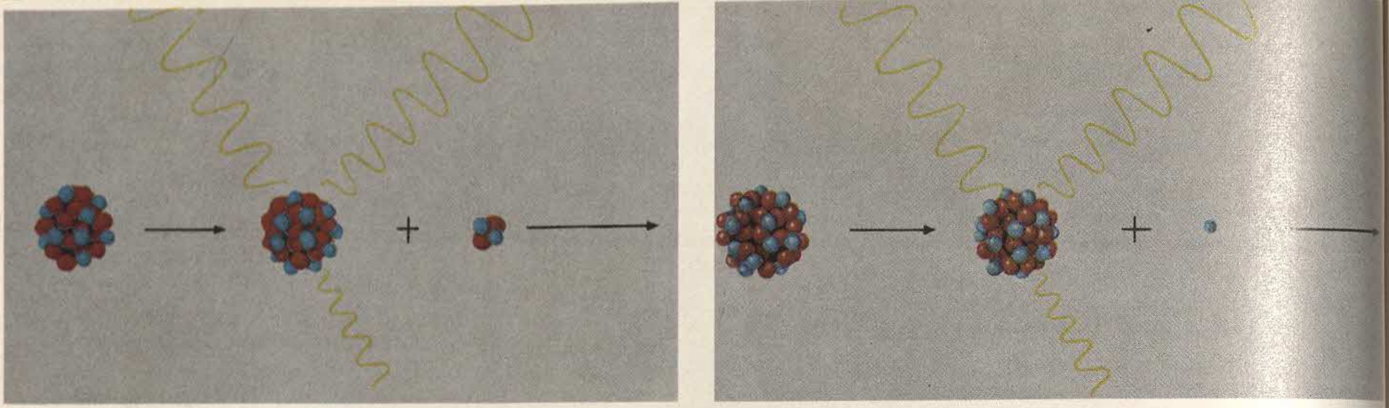


THE HALF-LIFE OF THE NEUTRON—If a neutron is isolated from the nucleus, it will decay and be changed into a proton and an electron; its half-life is just under 13 minutes.

RADIOACTIVE DECAY

A nucleus is said to undergo radioactive decay when it emits some of the particles of which it is composed or some of the products of change occurring within these particles. A substance composed of radioactive atoms thus emits particles or radiations; when these penetrate matter that surrounds the radioactive substance—whether that matter is the air or a solid object in which the substance is located—the atoms of the penetrated matter will be damaged. Specifically, the particles will capture electrons from, or ionize, the atoms of the penetrated matter.

The discovery of the existence of radioactive substances, made by Antoine Henri Bacquerel in 1896, resulted from this property of the emission of radiation. Becquerel had placed a piece of pitch-



5a

5b

RADIOACTIVE DECAY—Unstable nuclei are altered (disintegrate) in order to become stable. This occurs through the emission of an alpha particle, which consists of two neutrons and two protons (Illustration 5a); or a beta particle, which is an electron (Illustration 5b), as well as gamma rays, which are electromagnetic radiations of extremely short wavelength.

blende (a mineral containing uranium) on a photographic plate; he later found the plate darkened at the area of contact with the pitchblende. This property of darkening photographic emulsions is characteristic of ionizing particles emitted by radioactive substances.

TYPES OF RADIOACTIVE DECAY

Some nuclei of radioactive substances emit alpha particles, which consist of two neutrons and two protons and are, therefore, identical with the nuclei of the element helium. The nucleus that emits alpha particles thus loses four units of mass and two positive electrical charges. Uranium-238 is an example of an element whose nucleus emits alpha particles.

Other nuclei emit beta particles, which have negligible mass and one negative electrical charge, and which can be shown to be electrons. Such nuclei lose no mass and gain one positive charge (or, what amounts to the same thing, lose one negative charge). An example of an element with a nucleus that emits beta particles is potassium-10, an isotope that constitutes about one part in 10,000 of the weight of naturally occurring potassium.

Nuclei that undergo radioactive disintegration and emit either an alpha particle or a beta particle are disturbed by the loss of the particle and are caused to agitate or vibrate, expending energy that may be emitted in the form of electromagnetic radiation with a wavelength shorter than that of visible light, ultraviolet light, or even most x-rays. This radiation, known as gamma rays, is not always emitted spontaneously from the nuclei, but usually as a consequence of the energy remaining in the nuclei following emission of alpha or beta particles in the process of disintegration.

THE LIFE OF RADIOACTIVE NUCLEI

All radioactive nuclei approach, through one or more successive radioactive disintegrations, a state of nuclear stability, with a rapidity that varies according to the properties of the nucleus involved. Some radioactive nuclei have been observed with a very high probability of disintegration, and so are characterized as relatively unstable. Even if the stability or instability of a nucleus is known, however, it is not possible to determine whether or not the nucleus in question will remain stable for a short time or a long time; the probability of disintegration and the duration of disintegration are different and unrelated characteristics. A nucleus may have a high probability of disintegration—that is, be very unstable—and yet last for millions of years without disintegrating; or it may have a low probability—that is, be very stable—and yet disintegrate within a few seconds or even within a fraction of a second.

In order to express mathematically the characteristics of the speed of radioactive decay, it need only be stated that the number of nuclei of a given element that will decay in one second is proportional to the number of nuclei involved and also to a number, known as the "decay constant" and designated by the letter lambda (λ), that is an index of their instability. The greater the decay constant, the greater the number of nuclei that will disintegrate per second; more precisely, $dN = \lambda N\, dt$, where dN is the number of atoms that disintegrate in a time dt, λ is the decay constant, and N is the number of nuclei.

An alternative method of measuring the speed of decay of radioactive nuclei consists in determining the time required before the number of nuclei present in a given quantity of the substance in question is halved as a result of disintegration. This time is described as the *half-life*. Among the elements—all with atomic numbers above 80—that are naturally radioactive, the half-life varies from one ten-millionth of a second to many billions of years. Such extremes are indeed staggering to contemplate.

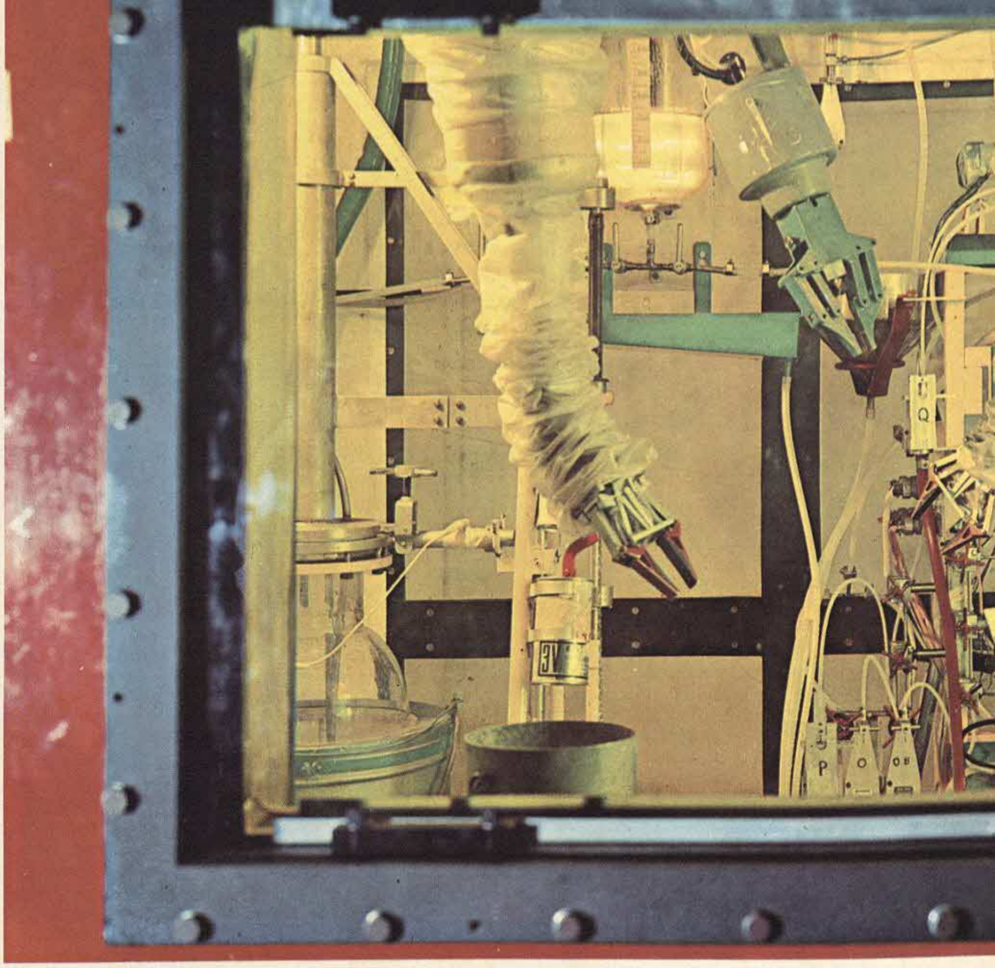
THE DECAY OF A MASS OF RADIOACTIVE SUBSTANCE

Thorium-232, a radioactive substance found in relative abundance in nature, has a half-life of 14 billion years; in other words, after that period of time, a given mass of this substance would be reduced by half. For example, if the Earth, when it was formed from solar or nebular matter, contained a certain quantity of thorium-232, it would still contain more than half of that quantity, because the Earth is not yet 14 billion years old.

On the other hand, a very different result occurs in a radioactive element with a much shorter half-life, such as radium, which has a half-life of 1,620 years. A mass of radium containing the number of grams corresponding to its atomic weight (226) would, under certain conditions, contain the number of atoms corresponding to the so-called Avogadro constant: 6.02×10^{23}. After 1,620 years, only half of these atoms would remain; after another 1,620 years, one half of this half (one quarter of the original number); after another 1,620 years, only one eighth, and so forth. How many atoms would remain after a very long time? This is easy to calculate: after a period of time corresponding to the half-life of radium there would remain (as has been seen) one half the quantity; after double the half-life, the quantity would be $\frac{1}{2}^2$; after 10 times the half-life, the quantity remaining would be

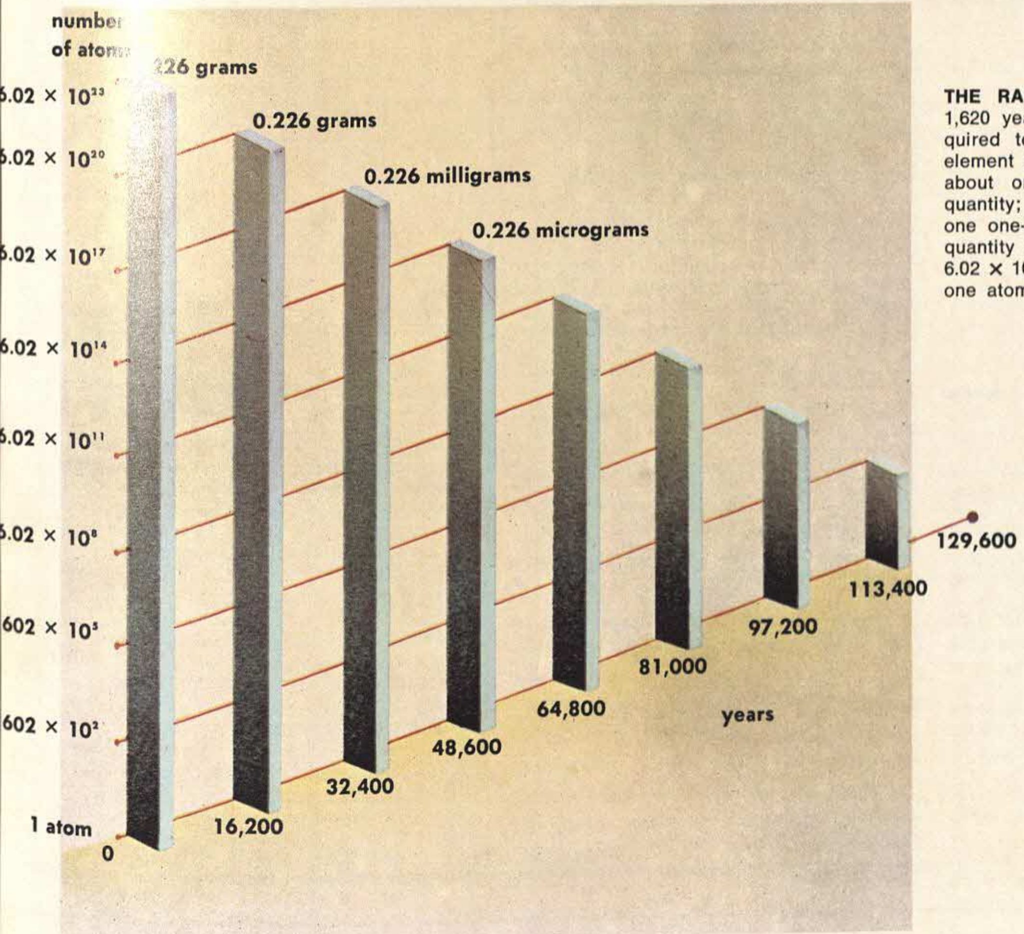
$\frac{1}{2}^{10}$ (approximately one one-thousandth); after 20 times the half-life, $\frac{1}{2}^{20}$ (about one one-millionth); after 30 times the half-life, $\frac{1}{2}^{30}$ (about one one-billionth), and so forth. With the passing of about 130,000 years, only a single atom out of the 602,000,000,000,000,000,000,000 atoms in the original 226 grams of radium would remain (Illustration 7).

Some radioactive elements decay far more rapidly than radium. In the case of thorium-224, for example, the number of atoms corresponding to the Avogadro constant would decay into a single atom within 1 minute and 20 seconds. The same result would be obtained in the case of polonium-213 in just under 0.0001 second. These radioactive elements do not exist in nature; they must be produced artificially when needed. In minute amounts, though, some "artificial" species are formed by radiation from space.



PROTECTION AGAINST RADIOACTIVE MATERIALS—The materials used in the field of nuclear physics are often radioactive and sometimes extremely dangerous. For this reason, physicists use equipment that enables them to handle dangerous substances by remote control. An example of such equipment is this pair of "mechanical hands," which operate behind a highly protective shield. →

7



THE RADIOACTIVE DECAY OF RADIUM—1,620 years—the half-life of radium—are required to reduce a given quantity of that element by half; 16,200 years to reduce it to about one one-thousandth of the original quantity; 32,400 years to reduce it to about one one-millionth, and so forth. If the initial quantity is 226 grams (which corresponds to 6.02×10^{23} atoms), after 129,600 years only one atom will remain.

THE RADIOACTIVE FAMILY | the unstable nuclei

The following fundamental question about radioactivity is often posed: why are some elements naturally radioactive and others not? The nature of the rays emitted and the heavy atomic weight of most naturally radioactive elements give physicists two highly important clues. The answer lies in the way in which subatomic particles are held together to make up the nucleus of an atom.

The study of nuclear structure shows that atomic nuclei remain stable only if they are made up of a limited number of nucleons. The unstable elements that decay by emission of a negative beta particle are those with nuclei having an excess of neutrons with respect to an optimal ratio. These excess neutrons in the nucleus transform themselves into protons by emitting an electron, and the nuclei thus become stable. Analogously, the nuclei that give rise to the emission of positive beta particles are too rich in protons and will transform themselves into stable nuclei when at least one of these protons transforms itself into a neutron. Lastly, the heavy elements—those having an atomic number above 80—are unstable by virtue of the emission of alpha particles.

The nuclei of uranium, radium, and other radioactive elements are continually decaying. The alpha and beta particles emitted are products of spontaneous decay in which heavy atoms break down into slightly lighter ones.

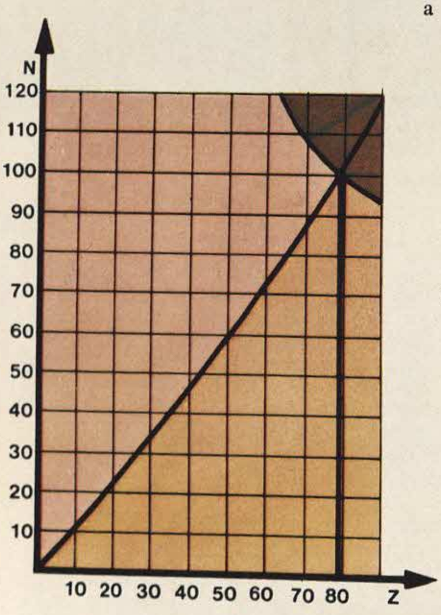
1

TABLE OF NATURALLY DECAYING NUCLEI—Illustration 1a is a Cartesian coordinate system in which the possible nuclides are shown with their atomic number *Z* as the abscissa and the number of their neutrons *N* as the ordinate. The stable nuclei distribute themselves along the curve in Illustration 1a. If the tangent to the curve is drawn at the origin, the curve will always be above this tangent. In view of the fact that the abscissa represents the atomic number *Z* (the number of protons in the nucleus), and the ordinate the number of neutrons $N = A - Z$ (*A* is the mass number—the sum of the protons and neutrons in each nucleus), the fact that the curve remains always above the tangent signifies that as the atomic number increases, the number of neutrons must be equal to the number of protons in order to keep the nucleus united. The stable nuclei with small atomic numbers have approximately the same number of neutrons and protons; as the atomic number increases, the nuclei have a greater number of neutrons than protons. Above the curve of the stable nuclides are those nuclides that have an excess of neutrons with respect to the ratio that renders their nuclei stable; one of the neutrons they contain will thus tend to transform itself into a proton.

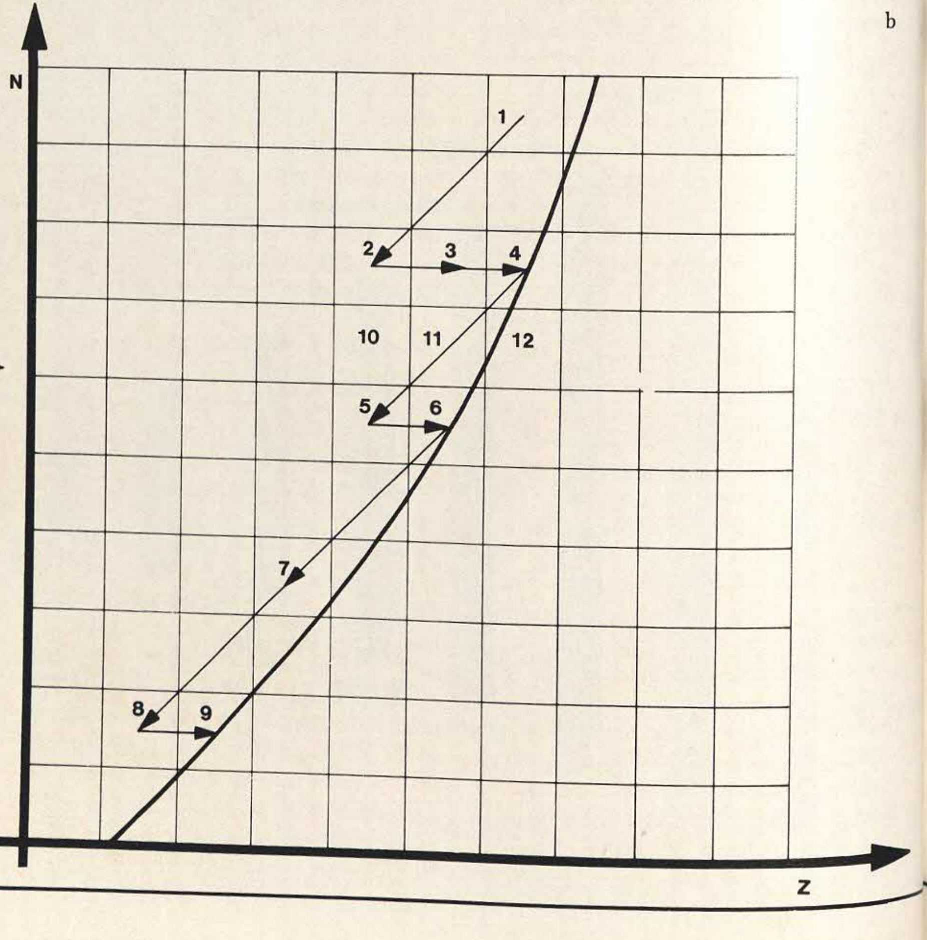
This is the type of radioactivity known as beta decay: a neutron transforms itself into a proton by liberating an electron. The nuclei that are found below the curve of the stable nuclei, on the other hand, have an excess of protons with respect to the optimal ratio; they therefore have a tendency to decay by emitting a positron (a positive electron); that is, a proton of the nucleus transforms itself into a neutron and the new nuclide will come to occupy a grid square with a position closer to the one that contains the curve of the stable nuclides. This kind of decay does not occur in natural nuclides. No nuclides with an excess of protons exist in nature, but they can be created artificially in certain experiments. Last is the area in the top righthand corner, which is separated from the rest of the graph by a curve that cuts across the curve of the stable nuclides; here are the nuclides that are unstable by virtue of the large number of nucleons they contain and that are subject to alpha decay. The boundary is not so precise as that shown because some nuclides subject to alpha decay also occur below it. These are exceptions, however; in addition, these nuclides have extremely long lives. Their half-lives exceed 10 million years, while the half-lives of the other nuclides range from one ten-millionth of a second to 10 million years.

Thus, natural radioactivity concerns the nuclides found above the curve of the stable nuclides. In a graph where *A* is plotted as the ordinate and *Z* as the abscissa (illustration 1c), this curve will be steeper than the bisector of the coordinate axes passing through the origin. It crosses the graph at approximately the slope of the dotted line. The nuclides subject to natural alpha decay are thus to be found above this line. A generic nuclide is represented by a grid square on this graph; in the course of alpha decay the nuclide loses two positive charges and two neutrons—four units of mass. Assuming that this nuclide was

a

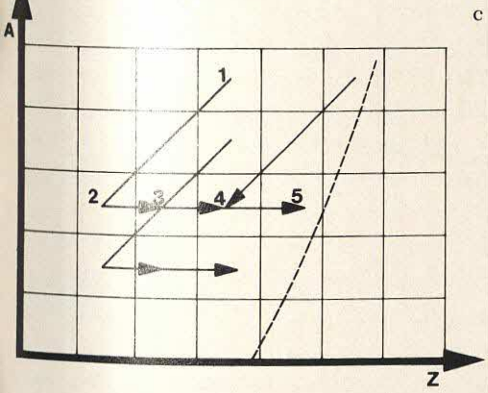


b



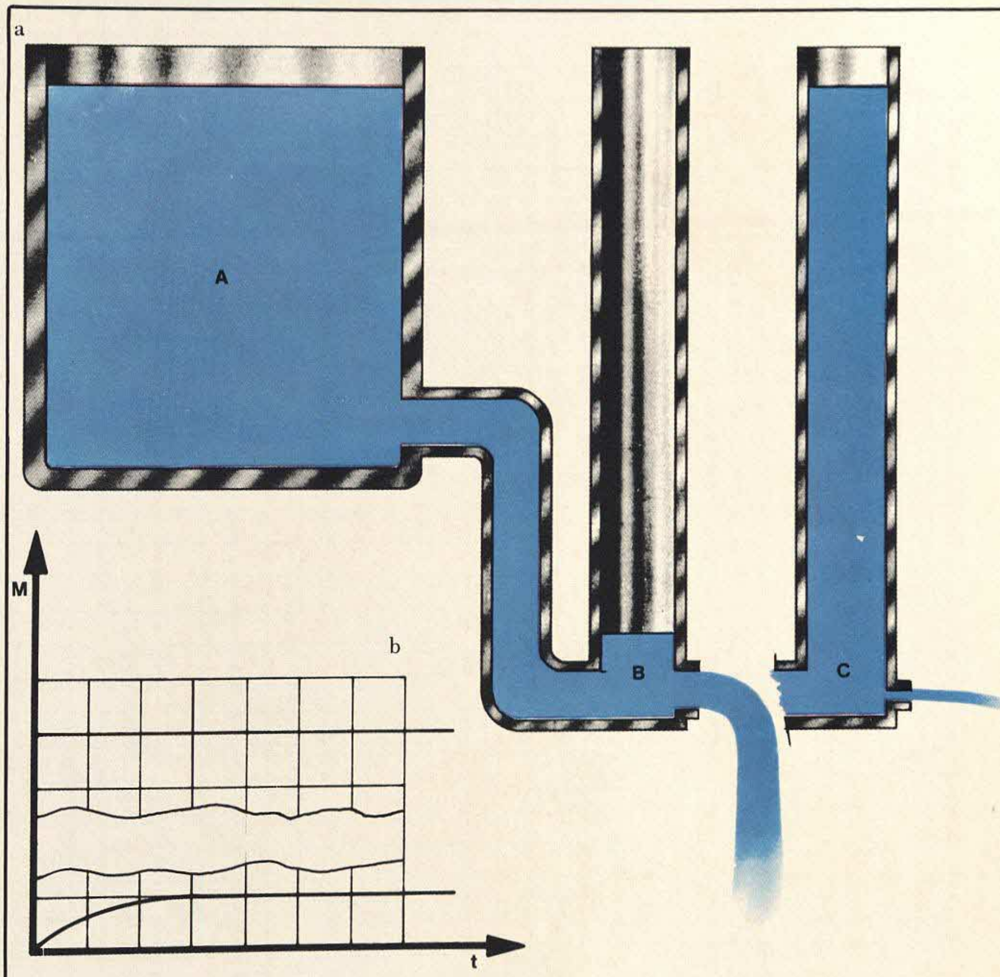
originally represented by the grid square marked 1, after the decay it will find itself in position 2. The trajectory of its descent as shown on the graph will have a slope of exactly 45° because it has lost an equal number of neutrons and positive charges. The grid square now representing the nuclide will thus be farther away from the curve of stable nuclides than the original one.

The nuclide has thus become very unstable as regards beta-negative disintegration; in effect, beta decay will now occur in the greater number of cases and will bring the nuclide closer to the curve of the stable nuclides. It thus passes from position 2 to position 3. If it is still too far away from the zone of stability, it may become subject to further decay that will bring it to positions 4 and 5 until it has lost its excess neutrons; but it still remains in the zone of instability subject to alpha decay and may, therefore, undergo further decay.



The graph in Illustration 1b shows that the alternation of alpha and beta decays in a chain of decay will not permit the nuclide to end up in a grid square chosen by chance. The nuclide that starts from grid square 1 follows a chain of alpha and beta decays and will arrive in grid square 2, later in 3, and so on right down to grid square 9. On the assumption that the various alpha and beta decays observed in this chain are put into a different order, the nucleus will descend by some other route and will find itself occupying other grid squares on its way; but it cannot arrive at all the grid squares. For example, the nuclide starting from grid square 1 can never arrive in grid squares 10, 11, or 12. This is due to the fact that it is impossible for the nuclide to vary its mass by a number of units other than 4, just as it is impossible for it to vary its charge by any number other than 1 (beta decay) or 2 (alpha decay).

2



RADIOACTIVE EQUILIBRIUM—Assume that a pure sample of a radioactive substance (of which the half-life t_1 is known) has been prepared. What happens when it decays into another radioactive substance that has a half-life $t_2 < t_1$? The daughter substance will decay less rapidly than the rate at which it is produced.

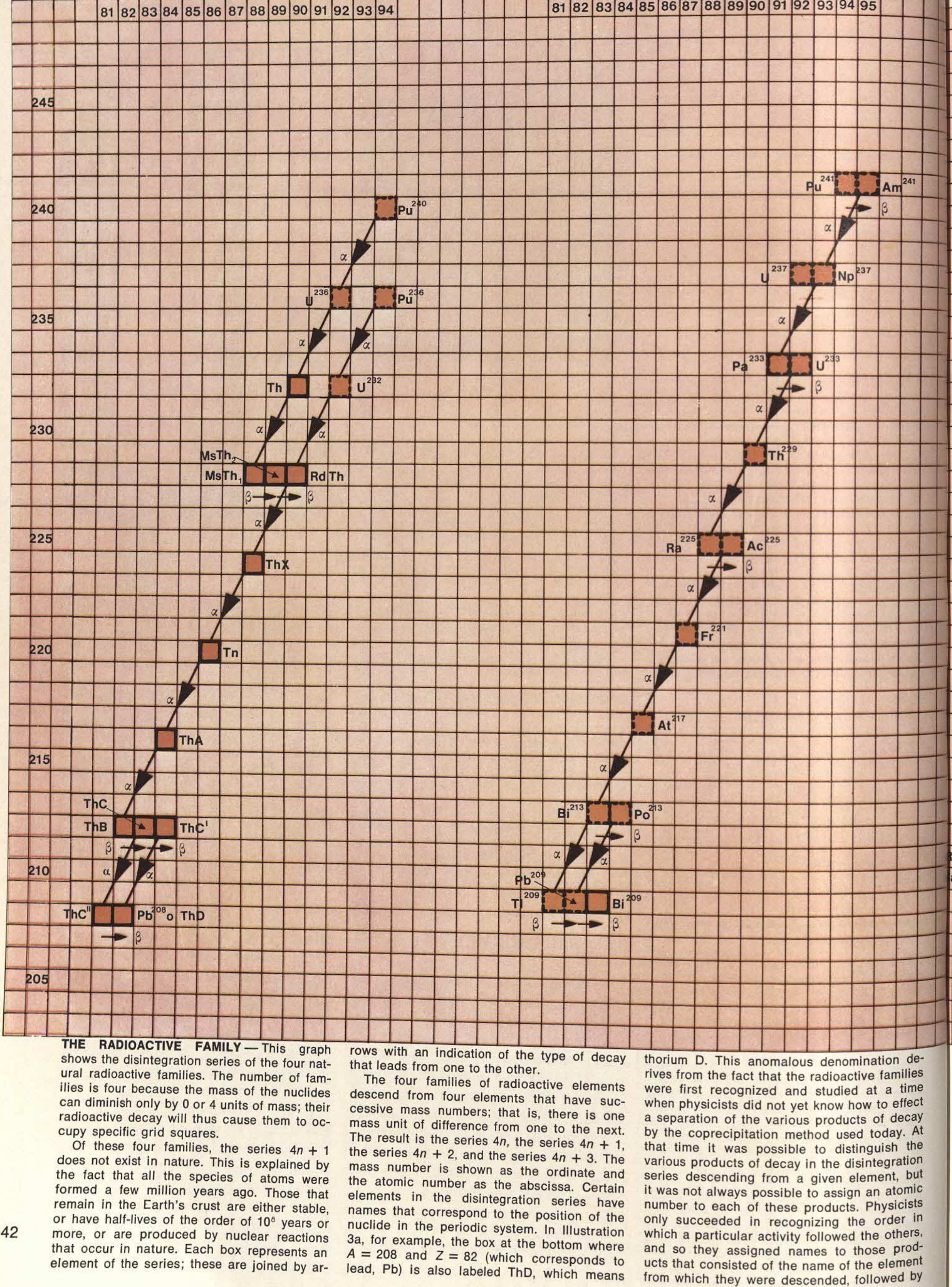
The situation can be visualized by imagining the parent substance to be a reservoir full of liquid **A** connected to another reservoir **B** that can discharge through a hole (Illustration 2a). If this hole is large, the supply of liquid arriving from the reservoir **A** will be discharged at once; very little liquid will accumulate in the reservoir **B.** If the hole in the second reservoir **C** is small, the liquid that represents the daughter substance will accumulate to some depth.

The horizontal line in the upper part of Illustration 2b represents the variation with respect to time of the mass of a weakly radioactive substance that generates a highly radioactive one. The first does not show any appreciable diminution, while the second will grow in percentage, become stationary, and maintain itself at a constant percentage of the mass of the mother substance.

NATURAL RADIOACTIVITY

The periodic table of the elements contains several elements whose nuclei are unstable by virtue of alpha decay. Because these elements occur in nature and decay spontaneously, they are called natural radioactive elements. Decay by means of alpha particle emission causes the new nucleus to be excessively rich in neutrons with respect to the proportion that would render it stable. An alpha-radioactive element will thus often generate a beta-radioactive element. Even after the emission of the electron of the second decay, the atomic number of the nucleus, although reduced, might still be greater than 80, and the new nucleus may, therefore, be subject to alpha decay. In this manner a chain of radioactive decay occurs. Decay by successive alpha and beta emissions, beginning from a certain element at the head of the series, can only lead to nuclides that are to be found at certain points in the table, and these depend only on the atomic weight of the parent element.

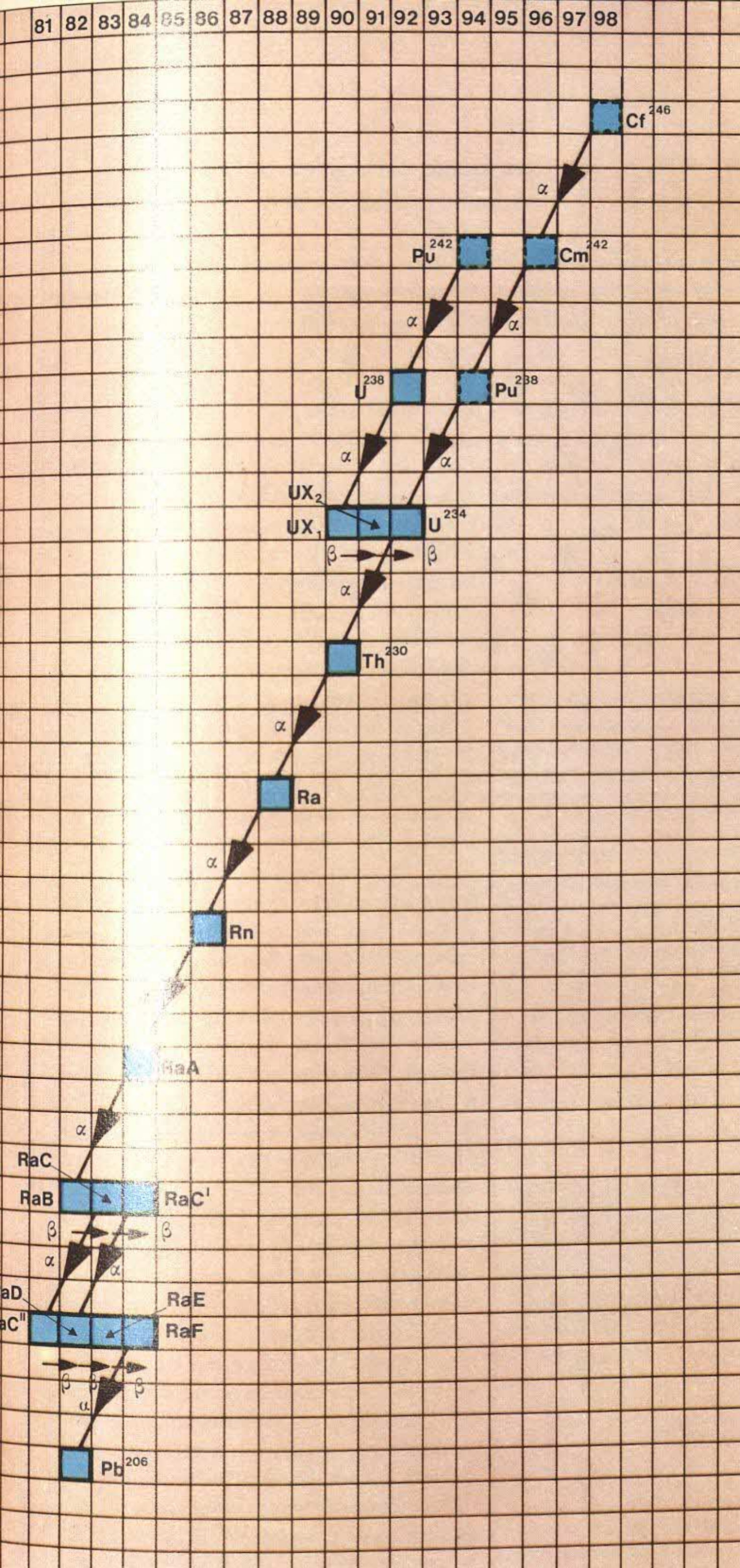
Lastly, it is interesting to consider the ratios that exist between the decay periods of the various nuclei that form the radioactive chain; these ratios determine the abundance in which each of the descendant nuclei is found. The ratios between the different elements of the chain are governed by the law of radioactive equilibrium.

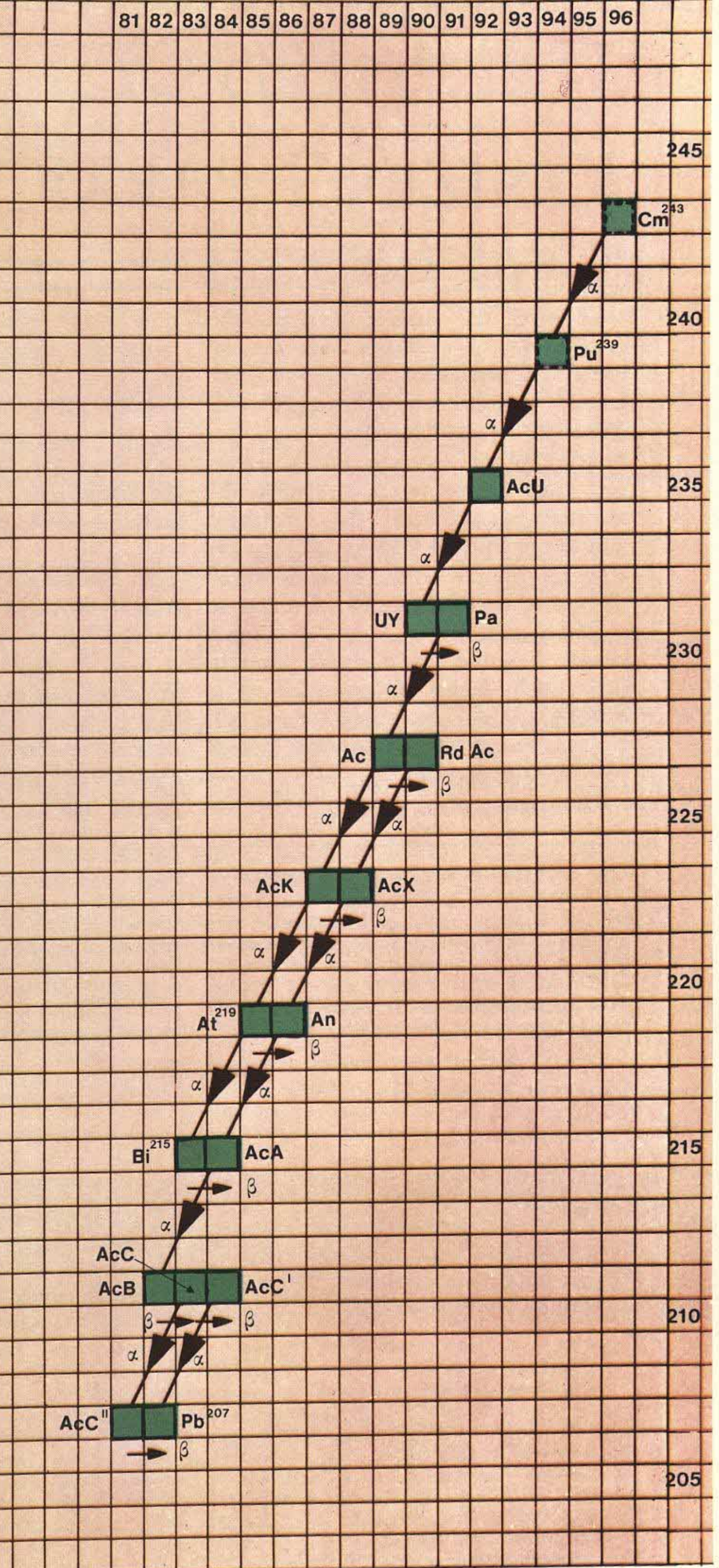


THE RADIOACTIVE FAMILY—This graph shows the disintegration series of the four natural radioactive families. The number of families is four because the mass of the nuclides can diminish only by 0 or 4 units of mass; their radioactive decay will thus cause them to occupy specific grid squares.

Of these four families, the series $4n + 1$ does not exist in nature. This is explained by the fact that all the species of atoms were formed a few million years ago. Those that remain in the Earth's crust are either stable, or have half-lives of the order of 10^8 years or more, or are produced by nuclear reactions that occur in nature. Each box represents an element of the series; these are joined by arrows with an indication of the type of decay that leads from one to the other.

The four families of radioactive elements descend from four elements that have successive mass numbers; that is, there is one mass unit of difference from one to the next. The result is the series $4n$, the series $4n + 1$, the series $4n + 2$, and the series $4n + 3$. The mass number is shown as the ordinate and the atomic number as the abscissa. Certain elements in the disintegration series have names that correspond to the position of the nuclide in the periodic system. In Illustration 3a, for example, the box at the bottom where $A = 208$ and $Z = 82$ (which corresponds to lead, Pb) is also labeled ThD, which means thorium D. This anomalous denomination derives from the fact that the radioactive families were first recognized and studied at a time when physicists did not yet know how to effect a separation of the various products of decay by the coprecipitation method used today. At that time it was possible to distinguish the various products of decay in the disintegration series descending from a given element, but it was not always possible to assign an atomic number to each of these products. Physicists only succeeded in recognizing the order in which a particular activity followed the others, and so they assigned names to those products that consisted of the name of the element from which they were descended, followed by





a letter of the alphabet that indicated their position in the disintegration series. In the diagram, in fact, are found a succession of names such as ThA, ThC, ThC′, MsTh$_1$ (Ms stands for mesothorium, which follows thorium in the radioactive chain), MsTh$_2$, and so forth.

Illustration 3a shows the natural decay of the 4*n* or thorium family. The naturally occurring element from which this family descends is thorium-232; it would seem that in cosmic nuclear synthesis this element is derived from plutonium-240. However, this element has so short an average life that it is not found in nature. The final product is lead-208, which is stable. The interesting fact here is that the lead formed by the disintegration of thorium has an atomic weight of 208. In a sample of natural lead it is, therefore, possible to establish what part thorium has played in its formation. These considerations are particularly important in terrestrial and cosmic geochemistry.

Illustration 3b shows the natural decay of the 4*n* + 1 or neptunium family. The element from which this series descends does not exist in nature. The other elements of the chain are likewise not to be found in nature because they decay very rapidly and so cannot accumulate in any appreciable quantity.

Illustration 3c shows the decay of the 4*n* + 2 or uranium family. This series is descended from uranium-238, the more stable of the two uranium isotopes to be found in nature. The lead that represents the stable end product of this disintegration series has a mass of 206. In naturally occurring lead, the ratio between the 206 and the 208 isotopes is determined in order to establish the ratio between the two elements from which they descend.

Illustration 3d shows the decay of the 4*n* + 3 or actinium family. Actinium is the name of an element in the family. It has given its name to actinium-uranium, the highest element in this series to be found in nature; this is nothing other than uranium-235, one of the less abundant isotopes of natural uranium.

THE PATHS OF IONIZING PARTICLES

the basic principles of radiation and its effects

The radiologist who protects himself with lead-impregnated rubber gloves and apron, the nuclear physicist who manipulates his specimen with remote-controlled mechanical equipment from behind thick concrete walls, and the engineer who covers the core of a nuclear reactor with a concrete shield several feet thick—all are trying to contain the radiation issuing from the substances and the equipment with which they are working. This radiation, when absorbed in large quantities, can be fatal and so must be contained by means of suitable shields. Because the materials used to make such shields are expensive, it is essential to know just what thickness will contain the radiation and prevent it from reaching the operator.

The study of this radiation and its capacity to penetrate various materials concerns not only the technician responsible for the protection of those handling radioactive substances; it also concerns the physicist researching the nature of radiation. He is interested in investigating what happens when an ionizing particle penetrates matter—what happens to the particle and what happens to the matter it penetrates.

THE PENETRATION OF AN ATOM BY A CHARGED PARTICLE

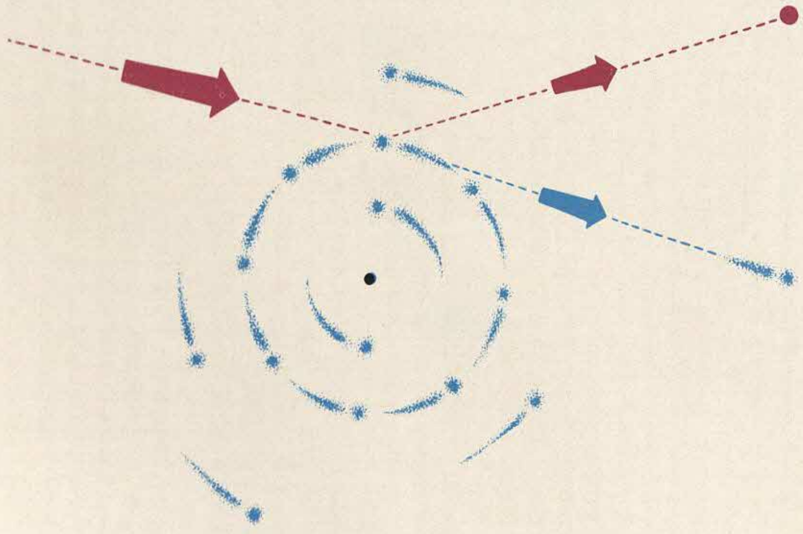
What happens to charged particles when they penetrate matter? The atoms that compose matter are rather close to one another, and may be likened to closely packed spheres. A charged particle—a proton, for example—that penetrates matter must find a way to penetrate these atomic spheres. The diameter of a proton is about 100,000 times smaller than that of an atom, and is relatively not much larger than that of one of the atom's electrons. The proton, therefore, finds the interior of the atom rather empty and has before it ample space through which to pass without colliding with any of the orbiting electrons. It must be remembered, however, that electrons and protons have opposite electrical charges and for that reason strongly attract one another. Thus, when a proton passes near an electron, the electrostatic attraction of the proton may deflect the electron from its orbit and away from the nucleus of the atom, to which the electron was already electrostatically attracted. In order to deflect an electron from its orbit and overcome the electron's attraction toward the nucleus, the proton must expend some of its own energy. This has the effect of slowing down the proton.

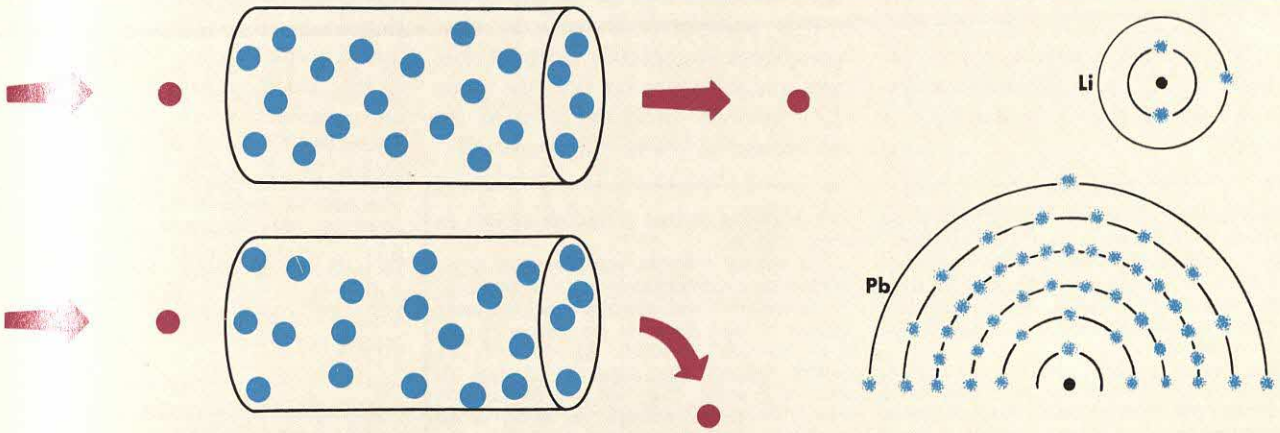
In its passage through matter, the proton penetrates many atoms; and although it does not attract electrons from all of them, it does attract a fair number. As a result of the gradual accumulation of electrons in its wake, the proton slows down little by little. Therefore, the speed of a charged particle, although very high at first, is eventually reduced to zero.

When a proton has attracted an electron away from an atom, that atom no longer remains neutral, for it has lost a negative charge—that of the electron; the amount of positive charge in the nucleus of the atom, therefore, exceeds the amount of negative charge orbiting around the nucleus.

An atom that has either lost or acquired one or more electrons is called an ion. The process of attracting an electron from an atom is known as ionization (ion-making). The proton, because of its properties as a positively charged particle, engages in ionization, and is so de-

LIKE A COMET IN THE SOLAR SYSTEM—The illustration shows a charged particle—a proton, for example, which is the nucleus of a hydrogen atom—passing through another atom. An atom resembles a miniature solar system, in which the place of the sun is taken by a heavy nucleus with a positive electrical charge and that of the planets by the electrons, which have negative electrical charges. The proton can pass between the electrons without colliding with them; if it does pass in this way, it will not slow down. However, if in passing it deflects one of these electrons from its orbital position, the intruding proton will expend some of its energy and continue on its way at a reduced speed.





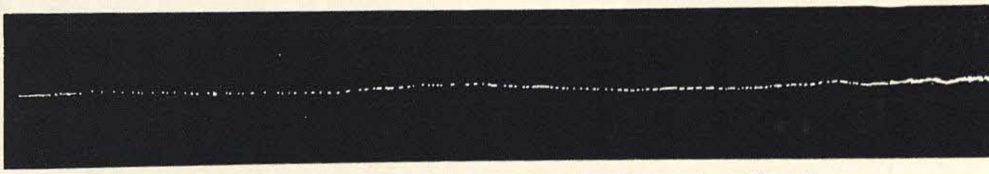
LIGHT AND HEAVY ATOMS: TWO DIFFERENT BRAKING EFFICIENCIES—The small cylinder at the top contains lithium atoms. A lithium atom has three electrons, each bound to the nucleus by a moderate force. If a proton penetrates this cylinder, it will not be braked to any great extent, because it would have to perform very little work in order to deflect the three electrons of a lithium atom. However, if a cylinder (below) of the same size is filled with the same number of lead atoms, a more efficient braking action is exercised on the ionizing particle that penetrates it. The particle will tend to deflect from a lead atom electrons that are bound more strongly to its nucleus than are the electrons of a lithium atom to its nucleus, because the electrons of the lead atom are closer to their nucleus. The positive electrical charge of a lead nucleus is greater than that of a lithium nucleus, because the lead nucleus has a greater number of protons, and these retain the electrons more strongly in orbit. Therefore, the ionizing particle would have to expend more energy to deflect an electron from the lead atom than would be needed to deflect an electron from an atom of lithium.

scribed as an ionizing particle. For the same reason, all particles with an electrical charge—protons, electrons, the nuclei of ionized atoms—are ionizing particles.

LEAD AS A SHIELD AGAINST RADIATION

In order to provide protection against ionizing radiation, the sources of such radiation—a nuclear reactor, for example, or a vessel containing radioactive material—must be separated from the endangered site by a thickness of material composed of heavy atoms, that is, atoms of high atomic number and therefore containing many electrons. Among the heavy elements that have proved suitable for shields against radiation, lead is the most effective and is used in all nuclear techniques. Lead is expensive, however, and in shields of the large size required for a nuclear reactor, lead is usually replaced by concrete into which scrap steel has been incorporated. Iron is less effective than lead, but it is only a tenth as expensive, and can, therefore, be used in far greater quantity.

Radiation shields are made of different materials, according to the kind of radiation that must be contained. The same nuclear process may produce different kinds of radiation, and in such cases the shield must consist of a series of layers of different thicknesses and different materials. In addition to iron and lead, barite is often used for this purpose. Barite, which occurs naturally and rather



A PROGRESSIVE BRAKING ACTION—If it were possible to observe a proton penetrate a piece of lead and produce ions there, the proton would be seen entering at high speed —almost that of light—and with an energy of 1,000 Mev (1 Gev). (The Mev, 1 million electron volts, is a measure of energy used in nuclear physics; its strength can be understood in comparison with the amount of energy needed to deflect an electron from an atom, which is estimated at between a few and 25 electron volts.) On entering the lead, the proton loses 12 Mev of energy for each centimeter of its progress. The density of the tiny dots appearing along its track (illustrated) is proportional to the number of ions it produces. This loss of energy slows it down (just as the leaves and branches of trees slow down a bullet fired into a forest); when the proton has lost half its energy, it will begin to lose 16 Mev for each succeeding centimeter, and by the time its energy has been reduced to the level of 300 Mev the rate of loss will be 20 Mev per centimeter. The more it slows down, the more effective the braking action becomes; at a speed permitting production of only 50 Mev of energy, its loss will be 70 Mev per centimeter, bringing it to a complete halt within that centimeter. This marks a limit beyond which the proton cannot penetrate.

abundantly, is an inexpensive mineral containing barium, an element with a high atomic number. The mineral is first ground into a powder, then mixed into the concrete from which the shields are made. A special problem exists where the weight of the shield must be considered, as in the case of the mobile nuclear reactors that serve as propulsion units for submarines.

THE IONIZING CAPACITY OF FAST AND SLOW PARTICLES

The ionizing capacity of a particle is directly correlated with its velocity. If the particle penetrates an atom at slow speed, it has enough time to attract electrons and jolt them far from the atom. If the particle passes the electrons too quickly to affect them with its attractive force, however, that force will not be sufficient to deflect the electrons from their attraction to the nucleus.

Protons and all other ionizing particles that penetrate matter are themselves deflected when they collide with a nucleus. Such a collision causes their paths to be erratic, and the slower the movement of the particle, the more erratic its path. Therefore, the track of a particle bends greatly at the end of its penetration, a phenomenon readily observed in all devices used to detect ionizing particles, such as the Wilson cloud chamber.

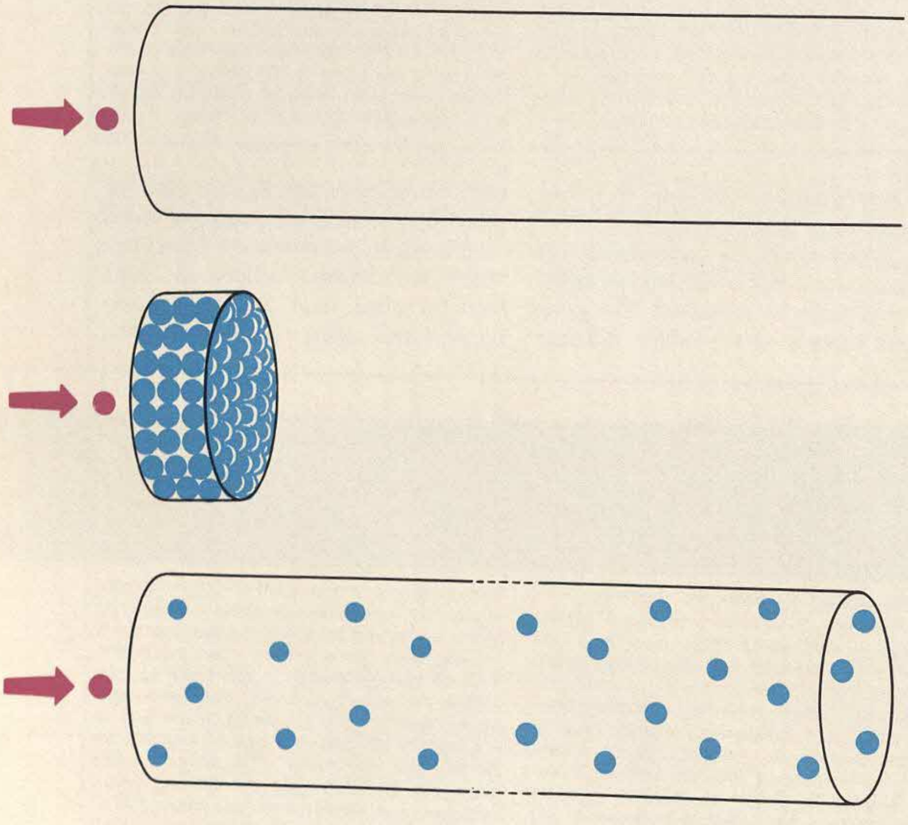
THE THICKNESS OF THE SHIELDS

A particle with a given charge and a given amount of energy penetrates a spe-

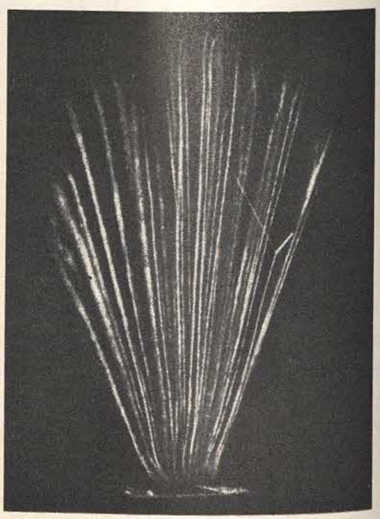
DENSITY AND BRAKING ACTION—The top cylinder, with a base area of 1 square centimeter, contains a vacuum. An ionizing particle (such as an alpha particle emitted by a radioactive atom) entering this cylinder encounters no obstacle and can travel an infinite distance.

The middle cylinder, with the same cross section as the top cylinder and a thickness of 1 millimeter, contains lead. The lead atoms, like those of all solids, are closely packed. This thickness of lead is enough to stop an alpha particle.

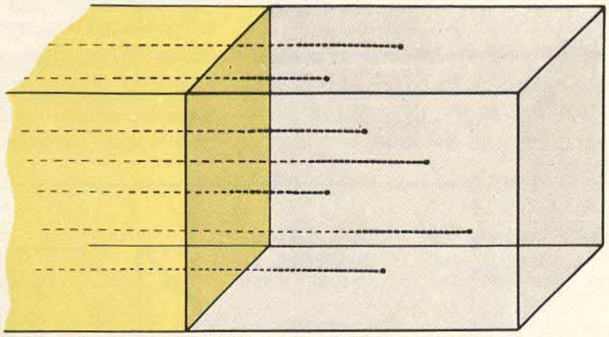
The bottom cylinder, with the same cross section as the others but with a thickness of 10 centimeters, also contains lead, the same number of lead atoms as the middle (1 mm-thick) cylinder. However, the atoms in the bottom cylinder are dispersed through its area, as in a gas. They will stop the penetration of the alpha particles, but further along the thickness of the cylinder.



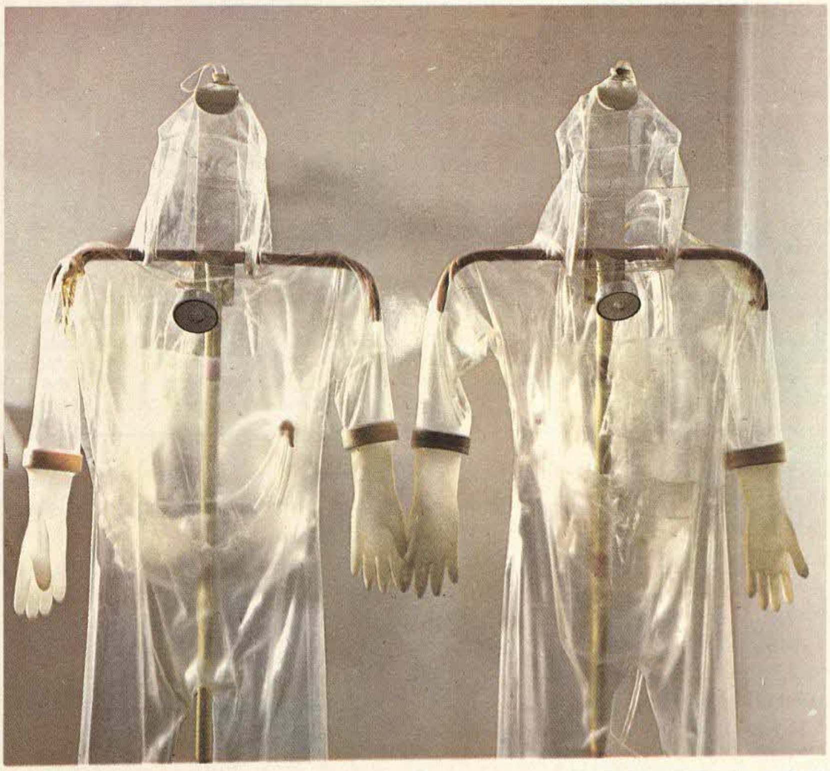
"STRAGGLING" OF PARTICLES IN A CLOUD CHAMBER—This photograph shows the tracks of alpha particles emitted in a cloud chamber. In this device, the tracks of the particles are made visible by the liquid droplets deposited around the ions produced by the particles as they penetrate air saturated with vapor. The distance of penetration depends on the energy of the particles and the density of the air. Although all the alpha particles emitted by any particular radioactive element have an identical amount of energy, it is evident that their ranges are not identical. The main reason for this is the fact that particles lose their energy by ionization at random along their trajectories; some particles are involved in fewer collisions, and therefore penetrate further, while others have more collisions—always at random—and come to a halt after less penetration. This phenomenon of range dispersion is known as "straggling."



A SECTION OF THE CORE OF A NUCLEAR REACTOR AND ITS SHIELD—Many radiations, including those of ionizing particles, emerge from a reactor. An effective shield can be designed if the nature and energy of these particles are known. The shield must have a thickness greater than the range of all the particles that must be contained. Many particles produce other radiations after they have stopped, particularly the highly dangerous gamma radiation. Inasmuch as these radiations do not originate in the reactor, but in the shield itself, the shield must be designed with enough thickness to absorb the additional radiations. The calculations involved in the design of a shield capable of absorbing all these kinds of radiation are extremely complex.



PROTECTION AGAINST RADIOACTIVE DUST—At times nuclear technicians must work in environments in which radioactive dust is suspended in the air. The radiation emitted by this dust does not have a range of more than 20 cm (about 8 in.) A suit of thin plastic material inflated with air is sufficient for protection. Inasmuch as the plastic material can keep out the radioactive dust and at least 20 cm of air separates the material of the inflated suit from the wearer, no radiation emitted by the dust can reach the wearer's body. Air is constantly introduced into the suit; this air flows out around the neck, the wrists, and any accidental holes, and serves to prevent any radioactive dust from penetrating these openings.



cific substance for a measurable distance. A table can be devised to show the possible depth of penetration of every kind of particle—proton, electron, alpha ray, and so forth—in a variety of materials, depending on the energy available. Tables of this kind are indispensable to those responsible for designing shields to contain radioactivity.

Instead of stating that an electron with the energy of 1 million electron volts (1 Mev) can penetrate so many centimeters of aluminum, it is customary to state that so many grams of aluminum with a cross section of 1 square centimeter can contain 1 Mev of energy.

Those who design shields needed to protect endangered sites from radioactive particles must know how far a particle with a given amount of energy can travel. If the relationship between the particle's energy and the distance it can travel—its range/energy ratio—is known, it is possible to calculate the energy involved whenever the range is measurable. In many experiments in nuclear physics, the possible distance a particle can travel within a given material is measured in order to determine the quantity of its energy.

FISSION | the principle of the atom bomb

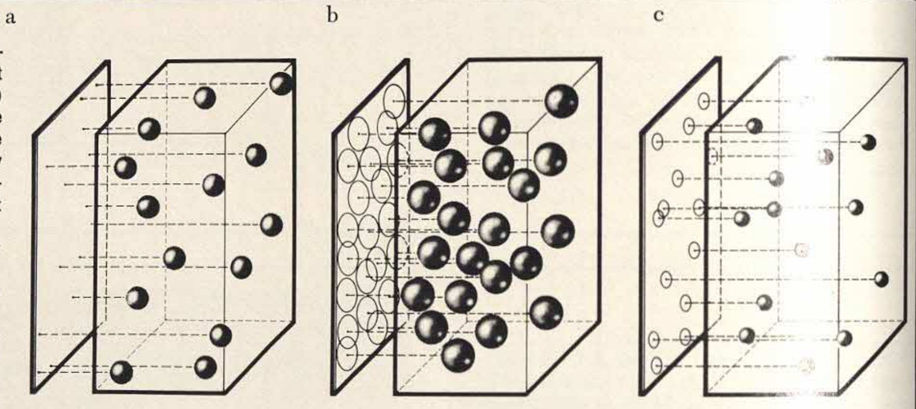
Early on the morning of August 6, 1945, a United States Air Force bomber released a single bomb over the Japanese city of Hiroshima. An instant later the first atomic bomb to be used in warfare exploded with the force of 20,000 tons of TNT, completely devastating a 4-square-mile area in the heart of the city, killing an estimated 66,000 persons and injuring 69,000 others. The atomic age had opened with terrifying reality. The first atom bomb represented the efforts of many men, perhaps most important among them the scientists who found a way to release a significant amount of energy from the atomic nucleus by the method of nuclear fission.

Between 1930 and 1939 physicists had subjected large numbers of atomic nuclei to bombardment by atomic particles in order to set off nuclear reactions. The particles used were of different natures and origins: alpha particles come from spontaneous disintegration of radioactive substances, while protons and neutrons come from nuclear reactions. The positively charged alpha particles have the advantage of possessing a relatively large mass (atomic mass units). Protons, because they have a positive charge of one and an atomic mass of one, were very easily accelerated by early types of particle accelerators. Lastly, neutrons—which, being neutral, cannot be accelerated electromagnetically—can approach an atomic nucleus without being affected by the negative charges of the electrons surrounding the nucleus. Neutrons can be produced by firing protons at other atoms. When deuterium, an isotope of hydrogen, is bombarded by protons, it is transformed into hydrogen and one neutron is ejected from the nucleus. Bombardment of beryllium with alpha particles provides another useful source of neutrons.

1

THE BARN—Suppose that inside a parallel-sided box there are atoms of an element, at a certain density. A diagram (Illustration 1a) can be drawn in which the centers of the nuclei of all the atoms of that element are shown projected onto a single plane. Now suppose this box is traversed by particles—neutrons, for example—that do not interact with the electrons of the atoms but only with their nuclei. (The electrons are so small that interaction with them is much less probable.)

Whether a neutron hits or misses a nucleus contained in the box depends on two factors: the density of the atoms in the box and the size of their nuclei. Small circles with dimensions corresponding to those of the nuclei can be drawn around the points representing the centers of the nuclei in the diagram. If these circles are large and frequent, parts of some circles will be superimposed (Illustration 1b). In this case a neutron traversing the matter in the box cannot avoid contact with the nuclei. If, however, the circles are small or widely spaced (Illustration 1c), the neutron will pass through because it is unlikely to meet any nuclei on its way. The conclusion is that the probability of fission occurring in the substance through which neutrons pass depends essentially on the dimensions of the nuclei and their density.



An important fact that must be taken into consideration in the study of nuclear reactions is that the nucleus of an atom is not a geometric entity as is a nucleus of microscopic dimensions. The sectional nature (the area of the circle shown in the diagram) of an atomic nucleus depends on two factors: the nature of the particle with which the nucleus interacts and the relative velocities of the particle and the nucleus. If these factors are known, it is possible to say that the nucleus will behave, in relation to the particular particle at the given velocity, as an obstacle of known geometric dimensions. This size is shown as the area of the ideal circle representing the hindrance of the nucleus to the passage of that particle. Since atomic nuclei are very small, an adequately small unit of surface area is required. The unit used is the barn, which has the value 10[illegible] cm^2. This unit is used to compare collision probabilities for different reactions, for given conditions of the incident particle.

In all the reactions studied up to 1939, the nuclei were bombarded with lightweight particles and underwent a change of mass of only a few atomic mass units. The nucleus absorbed the lightweight particle by which it was bombarded, and ejected particles having only a few atomic mass units.

In 1939 two German physicists, O. Hahn and F. Strassman, discovered that by bombarding uranium with slow neutrons (neutrons with an energy comparable to that with which the molecules move in a gas at normal temperature and pressure), particles could be obtained with a mass between that of the bombarded nucleus, uranium, and that of the bombarding neutron. The two physicists were certain that they had obtained a special kind of nuclear reaction, now known as fission, in which the target nucleus splits into two fragments of dimensions comparable to those of the nucleus itself. In the same year, the Austrian physicists, Lise Meitner and O. R. Frisch, succeeded in detecting, with an instrument known as a Wilson cloud chamber, the fragments produced by the fission of uranium nuclei.

While the energy released by chemical reactions results from the breaking of the bonds between two atoms or molecules and is of a magnitude of about one ev (electron volt) per atom, a uranium atom reacting to a single process of nuclear fission releases energy about 100 million times greater. Meitner and Frisch were able to measure the great energy released by such a reaction—about 100 Mev (million electron volts).

Meitner and Frisch also observed that during the process of fission of uranium nuclei, some neutrons were emitted that could cause other fission reactions inside the block of uranium—reactions known as chain reactions. Physicists then began to consider the possibility of exploiting this chain reaction to produce additional energy.

The first theory to explain the phenomenon of experimentally observed nuclear fission was advanced by the Danish physicist, Niels Bohr, and the American physicist, J. A. Wheeler. Even today this theory is incomplete because, despite all later improvements, it is still unable to explain all the phenomena of nuclear fission that can be observed experimentally.

2

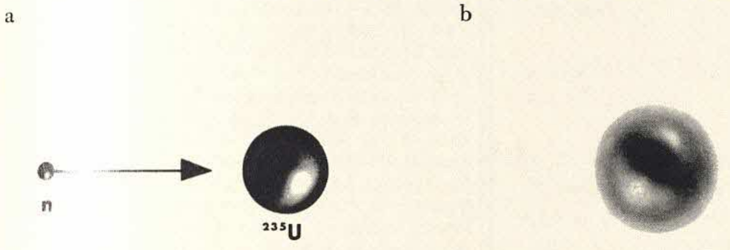
ENERGY EMITTED IN FISSION—The illustration shows how a fission reaction takes place when a heavy nucleus such as that of uranium-235 is bombarded (235 is the mass in atomic mass units). This fission reaction is used in both nuclear-electric power stations and atom bombs.

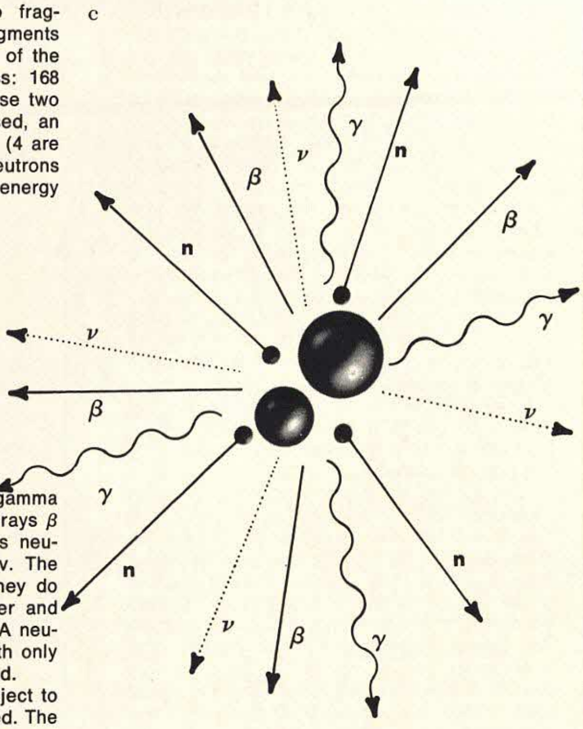
Illustration 2a shows neutron **n** approaching a ^{235}U nucleus at a velocity of about 2 km (about 1.2 mi) per second, a velocity comparable to that of a hydrogen atom (which has about the same mass as the neutron) in equilibrium with a gas at room temperature. The approaching neutron is therefore a thermal neutron.

In Illustration 2b the neutron has collided with the ^{235}U nucleus and formed a compound nucleus—that is, the nucleus and the incident neutron have fused, creating a new entity. The compound nucleus is unstable and will then decay after a short time, initiating the final state of the reaction.

Illustration 2c shows the compound nucleus undergoing fission—splitting into two fragments of unequal atomic mass. The fragments move rapidly, carrying with them most of the energy released in the fission process: 168 Mev (1 Mev + 10^6 ev). Along with these two fragments, some neutrons **n** are released, an average of 2.5 for each fission process (4 are shown in the illustration). These neutrons carry with them about 5 Mev of the energy released by fission. Also emitted are gamma rays γ with an energy of 10 Mev, beta rays β of 5 Mev and some particles known as neutrinos ν, which carry off about 11 Mev. The energy of the neutrinos is lost since they do not interact with the surrounding matter and are thus dispersed at a great distance. A neutrino may go right through the Earth with only a very slight chance of being absorbed.

Every time an atom of uranium is subject to fission an average of 199 Mev are emitted. The energy values given above are averages, and will thus vary from one fission process to the next.





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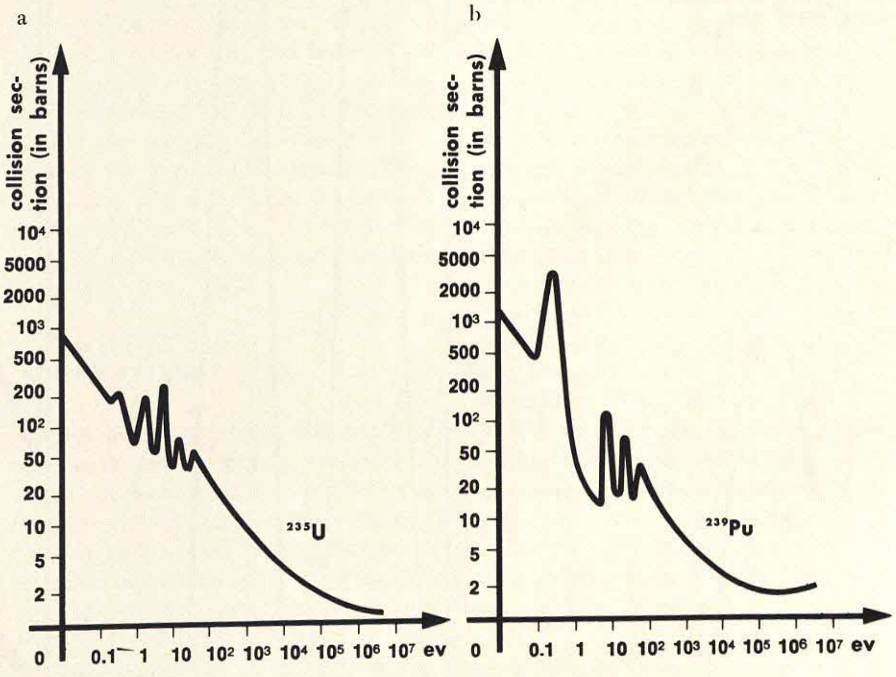
COLLISION SECTION OF THE FISSION PROCESS—The fission reaction can be produced in all nuclei with an atomic number above 30 when they are bombarded with neutrons having a sufficiently high energy charge. With nuclei having an atomic number above 30, the fission process is not particularly interesting because it takes place with absorption of energy—an endothermal reaction. Only nuclei with an atomic number above 90 will undergo fission with particles possessing less than 10 Mev of energy.

Few elements can undergo fission by slow neutrons. Interestingly, the nuclei of such elements all have an odd number of neutrons.

Other elements with high atomic numbers require neutrons with at least 1 Mev of energy for fission to take place. Even when the nucleus has been hit by the neutron, fission may still not take place, in which case an unstable composite nucleus is formed. Such a nucleus returns to its original state simply by emitting gamma rays, with no fission taking place.

The graphs show the collision section of uranium-235 (Illustration 3a) and plutonium-239 (Illustration 3b) for neutrons with different energy values. The collision section varies between extreme values when the energy of the incident neutron differs from the thermal energy at energy levels of a large number of Mev.



4

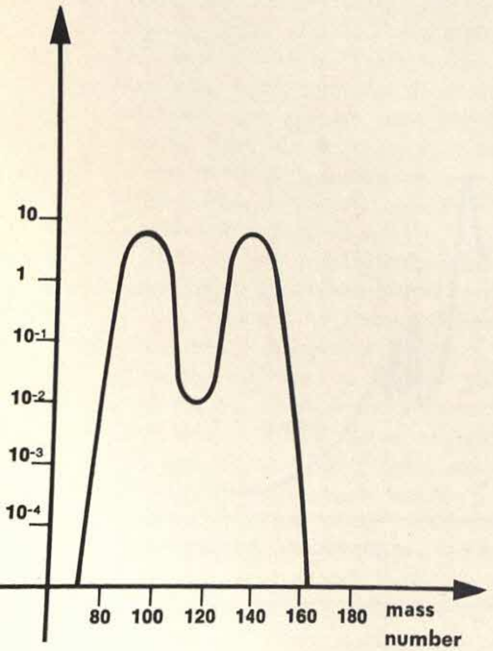
THE SYMMETRY OF FISSION FRAGMENTS—A characteristic of fission is that the two fragments into which the nucleus splits do not have the same atomic mass, and very rarely are the two masses close to half the mass of the original nucleus. The nucleus of uranium-235 usually splits into two fragments having masses of 95 and 140, or masses close to these values.

Illustration 4a shows the frequency with which the fragments of the ^{235}U nucleus are formed in relation to their mass number. (To show accurately the entire field of probability, a logarithmic scale is used for the ordinates.) The nucleus splits into two equal parts once every 10,000 collisions, an occurrence about 700 times less probable than a split into masses of 95 and 140.

Illustration 4b is the same graph divided linearly on a vertical scale, providing a clearer idea of the strongly asymmetrical nature of the masses in fission.

It is interesting to note that the two fission fragments are not stable. Their instability is due to the fact that for stability, a heavy nucleus, such as that of uranium, requires many more neutrons than protons, while the stable nuclei in the middle of the periodic system have only a few more neutrons than protons. The fission fragments are thus created with a large excess of neutrons, which renders them unstable with a strong tendency to decay back to their original state, emitting negative beta particles in the process. This explains why the products of fission are extremely dangerous: they decay very rapidly into stable elements. As fission products decay, they form fairly complex chains of unstable elements which emit large quantities of dangerous gamma and beta rays. Nuclear reactors must be adequately shielded to protect workers against these rays.

a



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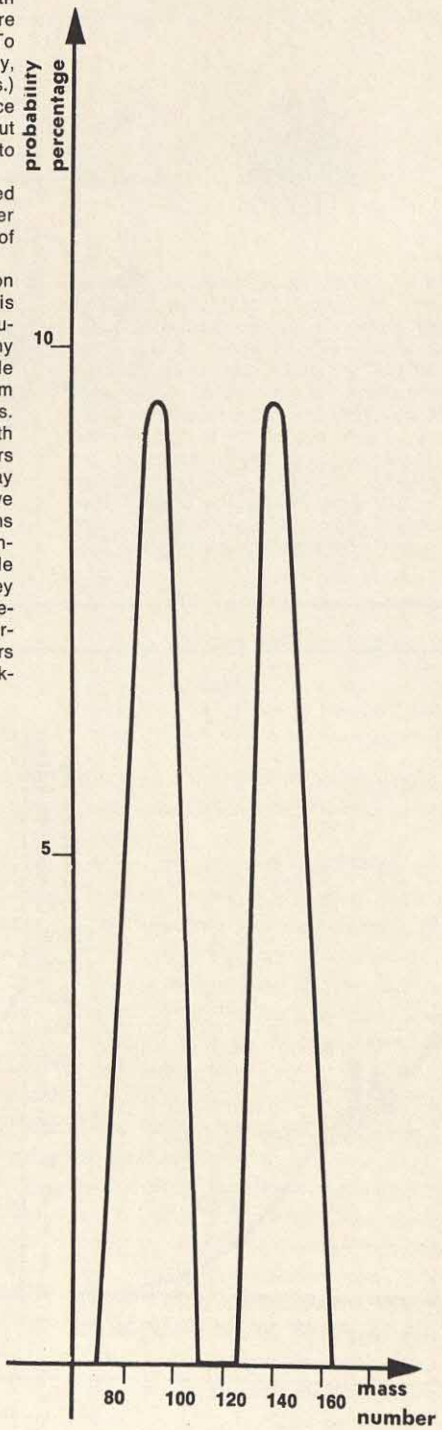


5

THE THEORY OF FISSION—The explanation of fission as a nuclear reaction requires, as do many other nuclear reactions, the theoretical presence of an excited compound nucleus.

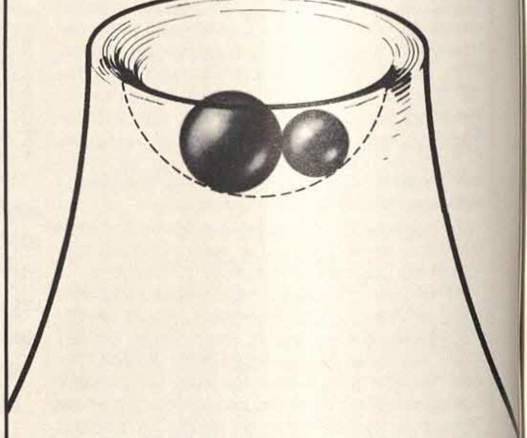
A nuclear excitation capable of causing fission can, however, be brought about by means other than slow neutrons. For example, fission may take place because the nucleus absorbs a gamma photon having a very high energy level. The theories put forward to explain the phenomena of nuclear fission are very complex; the following explanations give a general idea of the more simple theories.

One way of explaining the fission process is to imagine that the fissionable nucleus consists of the two fragments inside a potential barrier. A mechanical model, as in Illustration 5a, is that of two spheres, placed in the mouth of a crater, and free to oscillate. If the kinetic energy of the two spheres is less than the difference in potential energy between the bottom and mouth of the crater, the spheres would be unable to emerge, according to the laws of classical mechanics; yet this possibility does exist in quantum mechanics. By applying quantum mechanics to this model it is possible to calculate certain characteristic magnitudes of the fission, such as the energies possessed by the fragments.

A second theory of fission (Illustration 5b) uses the model of the liquid drop to study the oscillations of the compound nucleus—oscillations that can lead to fragmentation into two drops.

However, neither of these nuclear models can explain the asymmetry of the masses of the fission fragments. Present knowledge of the structure of the atomic nucleus provides a detailed, but still incomplete, picture.

a



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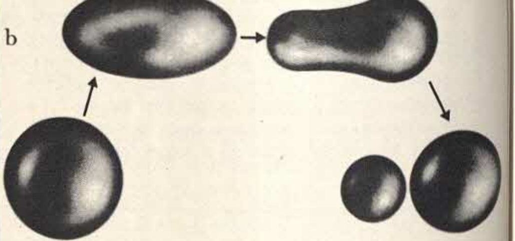


QUARKS

a vanguard hypothesis about the composition of baryons and mesons

The extraordinary complexity of the series of baryons and mesons suggests that they represent the aspect of the excited states of some subnucleonic entity. This hypothesis is readily suggested by a comparison of the baryon series with the series of microscopic entities of which matter is known to be composed. In the electromagnetic spectrum appear infrared rays emitted as manifestations of molecular energy, visible light and x-rays emitted as manifestations of atomic energy, and gamma rays emitted as manifestations of nuclear energy. Each manifestation is accounted for by the fact that there exist particles bound together by a force and constituting a system with energy content; variations of this energy cause the emissions of discrete entities of energy, of interchanges outside of the system, but always in accordance with the laws of quantization, that is, of a discrete emission of the energy itself.

In every instance, at least on the atomic and molecular levels, there is a simple relationship between the force and the field—in both the atomic and molecular instances, with the electromagnetic field. No complexity is introduced in descending the scale from the molecular to the atomic level, because atoms are relatively less complex than molecules; the latter are, in fact, far more varied than atoms and can, moreover, be composed of many more entities than can atoms, which contain only the nucleus and electrons. Consideration of the atom and the force that maintains it as an entity, therefore, tends toward simplification and clarification of the entities that compose the atom. In the instance of the nucleus, however, the force that maintains it as an entity is far more complex than the electromagnetic force and is so far almost entirely unknown.

The quanta of this nuclear force are the mesons, just as the quanta of the electromagnetic field of force are the photons. Although photons are nonmaterial particles, mesons have a rest mass and, in the last analysis, prove to be excited states of electrons. Descending the levels from the more complex to the ultimate components of matter, a degree of simplification is expected, because the bodies appear to be increasingly "elementary"; yet in a certain sense it seems that simplification recedes as the nuclear level is reached.

THE INTERNAL DYNAMICS OF THE NUCLEON

Actually, in the study of elementary particles an entirely exceptional phenomenon appears. Experiments have demonstrated that nucleons have an internal structure and that they may, therefore, be composed of even simpler bodies. Moreover, this hypothesis is suggested by analogy with the more complicated systems of atoms and molecules. When physicists stated that molecules were composed of simpler entities or that atoms were clusters of subatomic particles, all these particles had already been observed experimentally. However, nobody has ever been able to split the nucleon into simpler entities. One reason for this is that, even if it were possible, the splitting of the nucleon would require energy not yet available from existing accelerators. These are capable of producing energies of the order of 30 Bev (billion electron volts); perhaps they will need to produce in the range of 100 Bev (a 200-Bev accelerator is planned for Weston, Ill., and a 75-Bev accelerator was reported in operation in the Soviet Union), or even 1,000 Bev or more, in order to split nucleons into more elementary units.

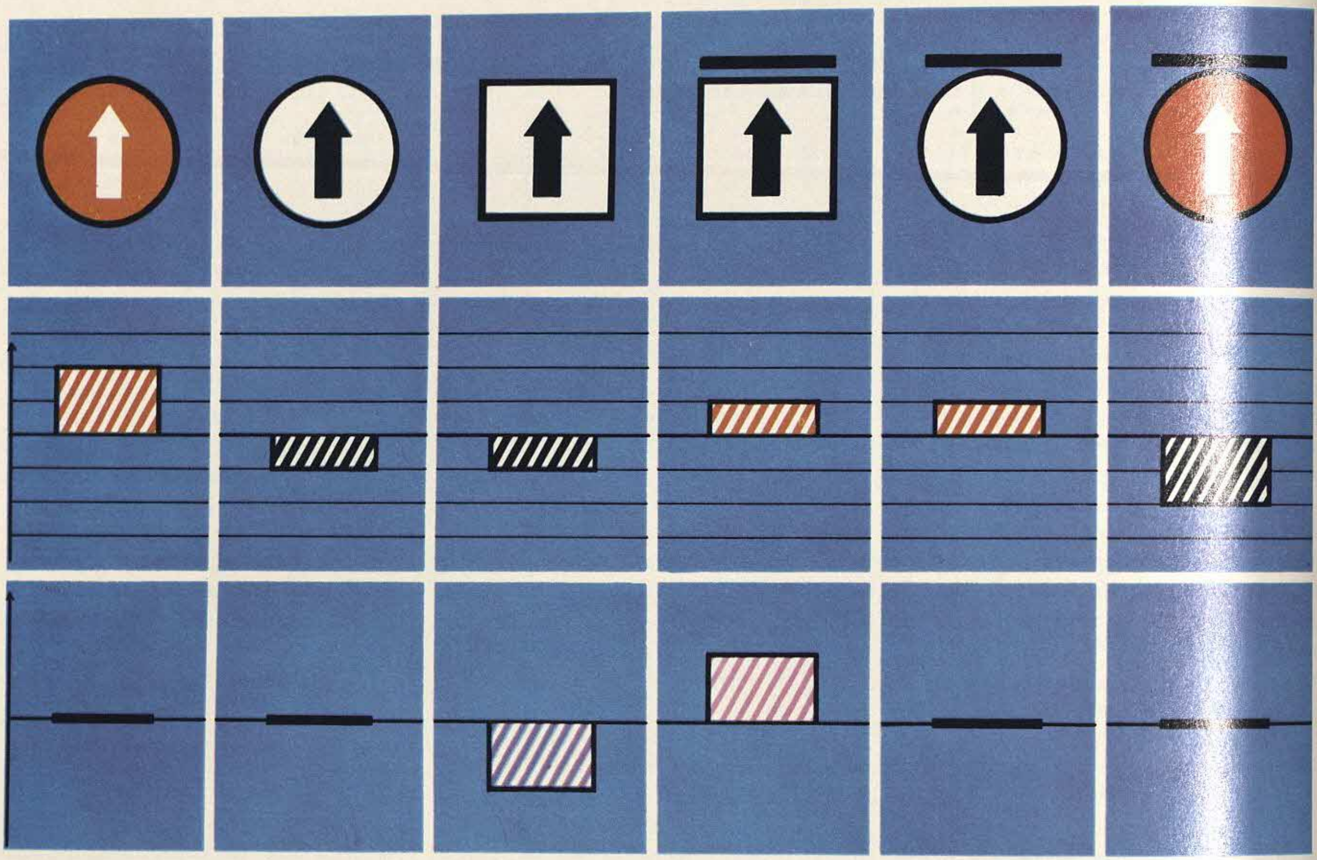
THE HYPOTHESIS OF THE QUARKS

Despite these difficulties, the study of the baryon series (that is, the series of excited nucleons) and the meson series (the series of excited electrons) has now reached such an advanced point as to present a rather clear picture and to suggest hypotheses concerning the basic properties of the entire series of baryons and mesons. Each of these particles has mass (although this property is of little importance, because it is readily changed by the presence of potential energy), electrical charge, spin, and strangeness. The task that physicists have set themselves is to discover theoretically what subnucleonic particles might explain the presence of the special features and characteristic numbers of all the components of the nucleus and of nucleons.

It was relatively easy to formulate this structure of the subnucleonic particle, but unfortunately this could only be done by means of particles that are very far from being as simple as more elementary particles of matter should be. These particles, or rather, these subnucleonic entities, have been given the generic name of quarks by the American physicist Murray Gell-Mann. Quarks have extraordinary properties. It must be noted first that only three such subnucleonic entities are required to explain all the phenomena of the dynamics of mesons and baryons. They are designated p, n, and λ (lambda). The first two, which have a number of similar properties, come to constitute a doublet state comparable to the proton and the neutron in the baryon series: the first is positively charged and has a value of +⅔; the second is negatively charged and has a value of −⅓. The third is also negatively charged and has a value of −⅓.

It must be remembered that the unit of electric charge is the electron, which has a value of −1. All three quarks have a spin of ½, but they have different values of strangeness: the first two have strangeness values of 0, but the third has a strangeness value of −1. It is postulated that antiquarks also exist; each of these has an electrical charge of equal but opposite value. The antiquark of p would have a negative charge of ⅔, the antiquarks of n and λ would have positive charges of ⅓, and the λ antiquark would have a strangeness value of +1.

It is possible to construct any particle in the baryon and meson series by combining quarks. Only two quarks are required to construct a meson, but three are needed to construct a baryon. Nothing has been said about the mass of quarks, because the mass of the particles of which the quarks are components—



THE THREE QUARKS AND THE THREE ANTIQUARKS—This illustration depicts the subnucleonic entities that compose every known particle except electrons and neutrinos. For the first time, in delving into the structure of matter, it is possible to represent the ultimate entity without making use of the commonsense image of a small sphere. Atoms and nucleons have properties that are intelligible in terms of the symmetrical form of a sphere; however, quarks are only known to be entities capable of clarifying numerical relations between simple numbers that represent the quantum numbers of the particles. It is, therefore, appropriate to represent quarks graphically by extremely simple geometrical symbols. These are presented in an order that divides the rows into two parts, left and right of the center, each part forming a mirror image of the other.

In the first row are the symbols of the quarks (on the left) and the antiquarks: p, n, λ, λ, n, p. The arrow in the center of each symbol represents the spin, with the value of ½ in each case. In the second row appear rectangles representing quantitatively and by location the charge corresponding to each of the particles; those above the median line are positive: +2/3, −1/3, −1/3, +1/3, +1/3, −2/3. In the third line appear similar rectangles representing the strangeness values: 0, 0, −1, +1, 0, 0.

Antiquarks differ from quarks by their opposite charge and strangeness values. Their function is to offer possible combinations to obtain antiparticles. In discussing the combination of quarks, therefore, normal quarks are understood, whereas a corresponding combination of antiquarks (those marked with a bar above) refers to the formation of antiparticles.

Quarks can be combined to form baryons and mesons. These combinations can explain all the properties of known particles except the electron and the neutrino. The hypothesis of the quark allows for a basic explanation of many properties of mesons and baryons, but it opens the question of the nature of the electrical charge, which, for the first time, is expressed in terms of a fraction of the charge of the electron. There is also development toward the complete disappearance of mass as a property of matter; mass appears only as the potential energy of the bond between quarks. Mass thus comes to lose the material aspect of a substance and is being replaced by a concept expressed completely in terms of energy.

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mesons and baryons—derives from the potential energy that is stored in the system of quark combinations.

Quarks possess a fractional charge, the first time this phenomenon has been encountered in the study of physical systems. This altogether new fact is not in accord with the tenets of physics, and it has not been possible to justify the fact that no particle previously discovered had a charge less than that of an electron.

The hypothesis of the quark evidently makes it possible to explain many of the properties of baryons and mesons, especially those connected with the concepts of spin and strangeness. Nevertheless, this hypothesis is still undeveloped; the origin of the forces that allow quarks to combine and form the more complex particles is not known, nor are the laws that govern these forces. It is not known whether quarks may be detached from one another or whether they have independent existence, even for extremely short periods, nor is it known what energy would be required to attempt to discover these things.

Even more important questions can be raised to bring to light the relationships between quarks and the particles that physicists previously considered more elementary than the electron and the neutron. As each new accelerator of higher energy is built, early experiments are sure to include quark searches.

ANTIMATTER | the anti-universe and its unlikely existence

The microscopic systems, such as the atomic and nuclear systems, are governed by laws of action and reaction described in an equation devised by the Austrian physicist Erwin Schrödinger. This equation is actually a mathematical theory that makes it possible to deduce results that cannot be explained by means of classical mechanics.

Today's expanding knowledge of atomic and nuclear physics has given scientists as much confidence in the use of Schrödinger's equation and its derivatives as they have in Newtonian theories of mechanics for the calculation of the movements of celestial bodies or of any other macroscopic mechanism.

However, Schrödinger's equation itself has its limitations and its own realm of validity. In particular, it is inapplicable to situations possessing considerable amounts of energy—systems, for example, in which the particles move at speeds approaching the speed of light. In such cases consideration must be given to the relativistic factors, which have a great influence on the values of the total amount of energy present.

One equation which takes into account these relativistic factors is named after the British physicist Paul Dirac, who deduced its form. An interesting property of this famous equation is that it has two types of solutions. One type corresponds to the regular particles with positive energies and a definite electric charge. The other solution, however, corresponds to particles with negative energies. The latter particles may be reinterpreted as physical particles with positive energies, but with (among other things) opposite charge to the first type of solution.

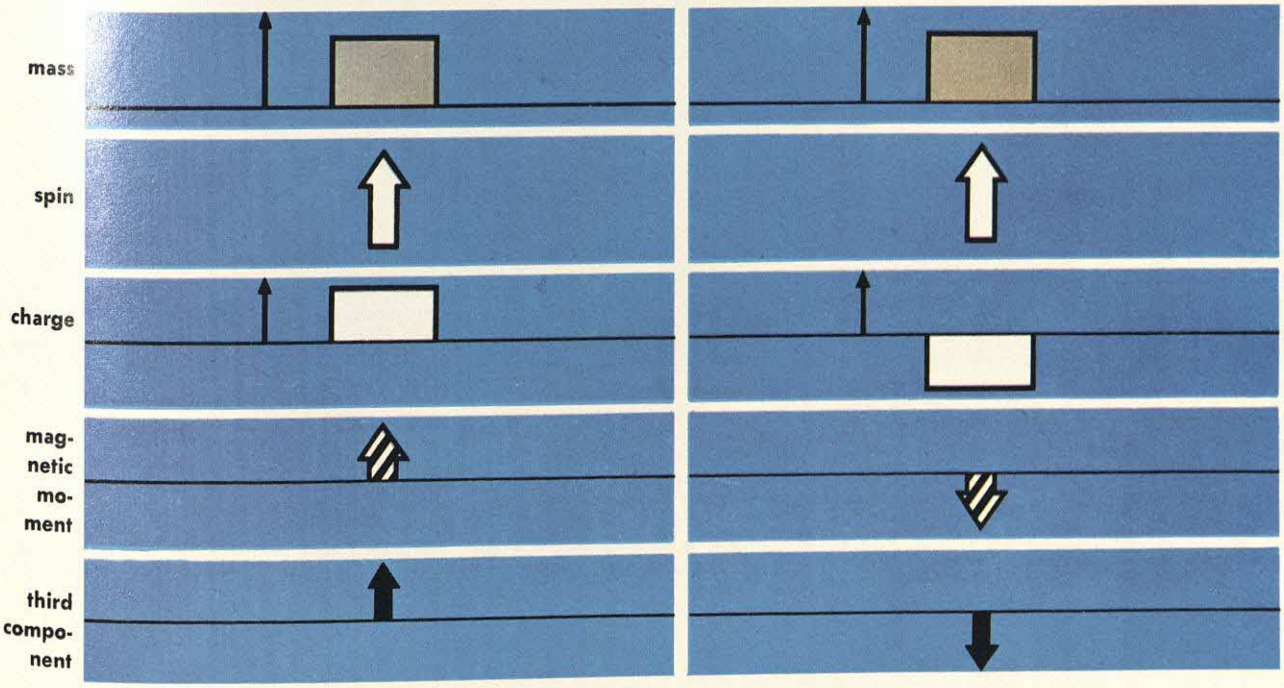
THE ANTIPARTICLES

In applying Dirac's equation to the case of electrons, the existence of a particle possessing the same properties as the elec-

PARTICLE AND ANTIPARTICLE — This table illustrates some properties of the particles that are the same or opposite in the corresponding antiparticles. Mass and isotopic spin are the same. The charge, however (always provided that a charged particle is being considered), changes sign; this is also true for the magnetic moment. In the case of an unstable particle (a meson, for example), the particle and its antiparticle have the same rate of decay. The value of the total isotopic spin remains unchanged, but the third component of the isotopic spin is opposite. It might seem from this table that the antiparticles are nothing other than the particles themselves with the sign of the charge changed. The real situation, however, is usually much more complex because the structure of the particles is extremely complicated. The energy produced by the encounter of these particles can also be very great, and it may be possible for each of the two photons to materialize again into an electron-positron pair. For this to happen, however, each of the photons must have at least as much energy as is needed to create the mass of an electron-positron pair. The chain of reactions that follows from this is called an electromagnetic cascade.

In the mechanics of this annihilation, p is the momentum of the incoming positron and p' and p'' are the momenta of the two photons; therefore, $p' + p'' = p$.

The energy that is liberated in the annihilation of an electron-positron pair amounts to about 1 Mev. Two protons (positive and negative) can also annihilate themselves in exactly the same manner as a pair of electrons. In this case, the quantity of energy liberated in the annihilation is much greater and amounts to about 2 Bev. A subsequent cascade is likewise produced. In addition, the antiparticles exist also in the case of neutral particles. For example, the neutron has an antineutron. In other cases, again, the neutral particle and its conjugate have the same constitution; thus, it is its own antiparticle. A typical case of the latter situation is the neutral pi-meson.



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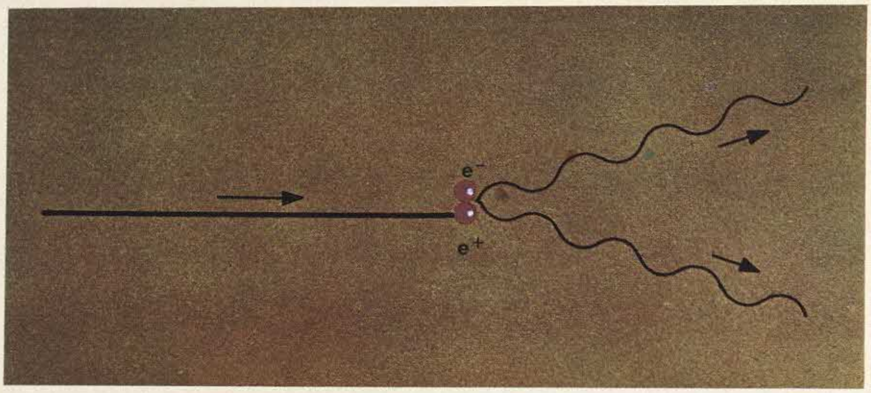


THE ANNIHILATION OF ANTIMATTER—A positron (antielectron) moving through ordinary matter will come close to an ordinary electron and will annihilate itself: in other words, the rest mass of the two particles will become completely annulled and will be wholly transformed into a pair of photons (following the principle of equivalence between mass and energy, $E = mc^2$). It is not possible for the electron and positron to annihilate into a single photon, for this latter process can be shown to violate the conservation of energy and momentum. The annihilation, therefore, takes the form of a transformation into a pair of photons, each of which possesses half the rest energy of the original particles plus half of such energy as they may have had at the moment of their encounter.

tron, but an opposite charge, and corresponding to the second type of solution, is anticipated. Such a particle is called the antielectron, the positive electron, or more simply, the positron. The positron was discovered by the American physicist C. D. Anderson, who found traces of its existence in a Wilson cloud chamber. Other physicists later constructed an improved cloud chamber whose space was checked only when an ionizing particle was signaled as being near it or even inside it. In other words, the chamber was sensitized only when some nuclear event was worth photographing. This created the possibility of photographing many positrons, and the new particle soon entered the ranks of the well-established ones.

In general, Dirac's equation predicts the existence of a large number of antiparticles, one for each particle. Thus, it becomes possible to speak of antimatter. If ordinary matter consists of particles, the antiparticles constitute something that can be called antimatter.

Many antiparticles have subsequently been observed experimentally. The discovery of these antiparticles highlighted one of their fundamental characteristics: they annihilate themselves whenever they encounter the particles of which they are the conjugates. The particle-antiparticle pair annul their mass, transforming it into energy, and produce electromagnetic or other kinds of radiation.

It follows, therefore, that the antiparticles—and, consequently, antimatter—are strongly unstable. While they can live indefinitely in a void, their life is extremely short in matter, due to their rapid annihilation. This means that one can imagine a universe composed of antimatter—a universe in which all the particles making up atoms and nuclei are the conjugates of the ordinary particles. In such a universe of antimatter, or anti-universe, the antimatter would be stable; the ordinary particles, on the other hand, would be unstable. They would encounter the antiparticles almost as soon as they were produced, and would become annihilated. The universe, which is made up of matter, thus appears only as a universe that has been chosen by chance to exist in the place of a universe of antimatter. There appears to be no preferential reason why one type of universe should exist rather than the other; and the reason can, therefore, be nothing other than a random chance.

ANTIMATTER AND ANTI-UNIVERSE

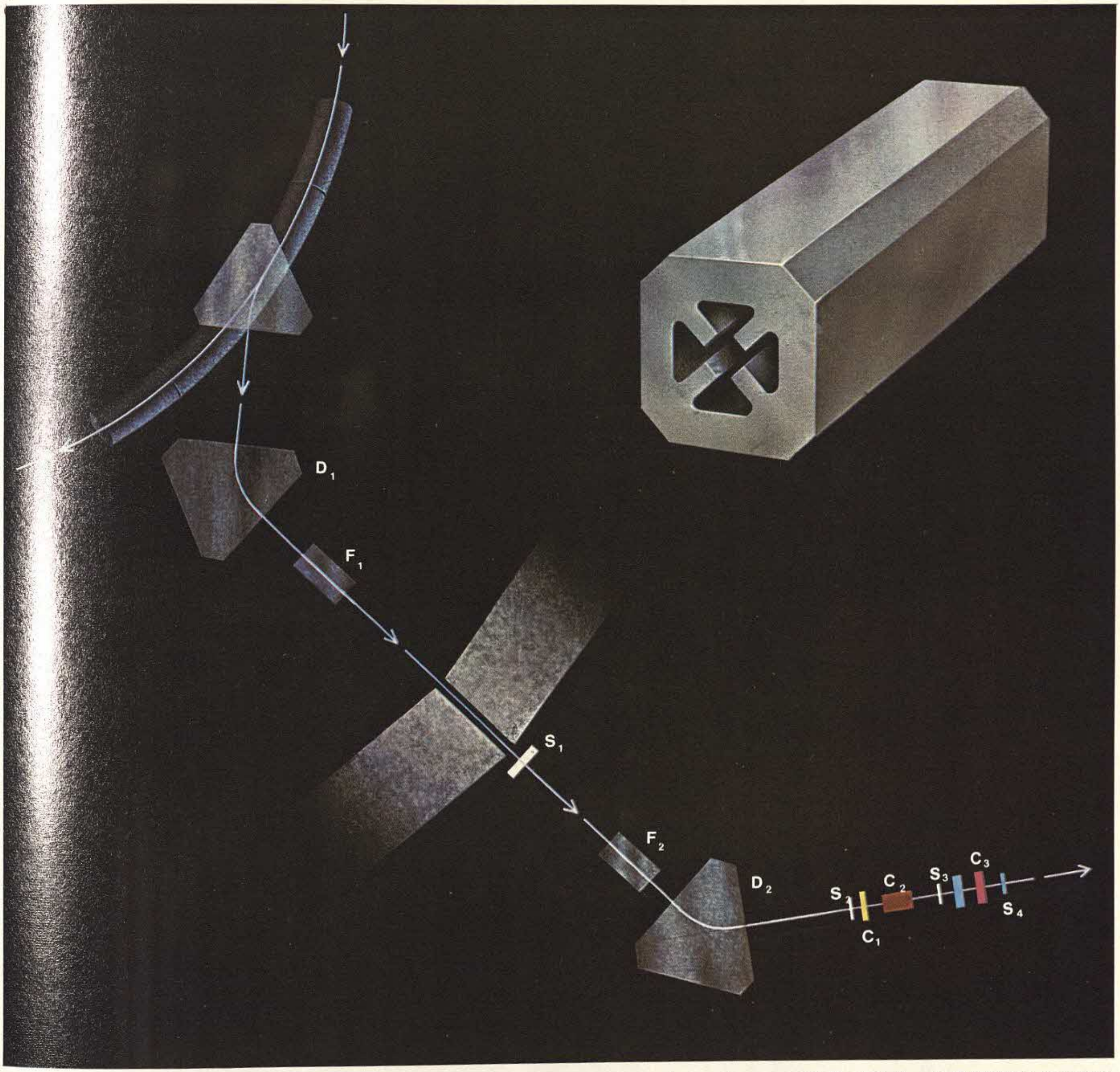
This perfect symmetry of matter and antimatter, of universe and anti-universe, has led to speculation that in some remote corner of the universe there might exist celestial bodies made up of antimatter and separated from our own planet by vast reaches of empty space. Such an anti-universe would be perfectly stable and capable of existence because, according to this line of thought, it would be safely separated from the ordinary matter of the rest of the universe.

An atom of antimatter would have a negatively charged nucleus composed of antiprotons and antineutrons surrounded by a cloud of positrons. In all its properties except those depending directly on the reversal of charge and magnetism, it would be identical with, and just as stable as, a normal atom of the same number of protons and neutrons: its energy levels would be precisely the same, and all its spectral lines would, therefore, be indistinguishable from those of the normal atom.

However, this hypothesis, dictated by considerations of symmetry, is probably not valid. In the known universe—and even in the so-called empty space that is believed to exist between the galaxies—ordinary matter always exists in an extremely rarefied state. This matter would be likely to encounter the antimatter of the antistars and would give rise to annihilations, producing intense emissions of energy capable of being recorded even on Earth.

In addition, many considerations of an astrophysical nature tend to exclude the existence of such an anti-universe.

3



THE PRODUCTION OF ANTIPARTICLES—The antiparticles can be produced in different ways, depending on their particular type. For example, positrons can be produced by a gamma ray passing close to a nucleus. If this gamma ray possesses sufficient energy, it will be capable of materializing into an electron-positron pair.

If the ray is to materialize into a proton-antiproton pair, the necessary energy must exceed an even higher threshold. The first successful experiments in this field were conducted by Chamberlain, Segrè, Wiegand, and Ypsilantis. The diagram shows the arrangement of the equipment with which the antiproton was discovered. In this equipment, **D_1** and **D_2** are the deflecting magnets; **F_1** and **F_2** are the focusing magnets; **S_1**, **S_2** and **S_3** are scintillation counters, and **C_1** and **C_2** are Cherenkov counters. The counters **S_1**, **S_2**, **S_3** and **C_2** are in coincidence, while **C_1** is in anticoincidence. This arrangement ensures that the signals reaching **S_3** are the ones produced by the antiproton.

Results of the first measurements of the mass of the antiproton showed that the antiproton possessed a mass about equal to that of the proton.

AVOGADRO'S CONSTANT | when N equals 6.02×10^{23}

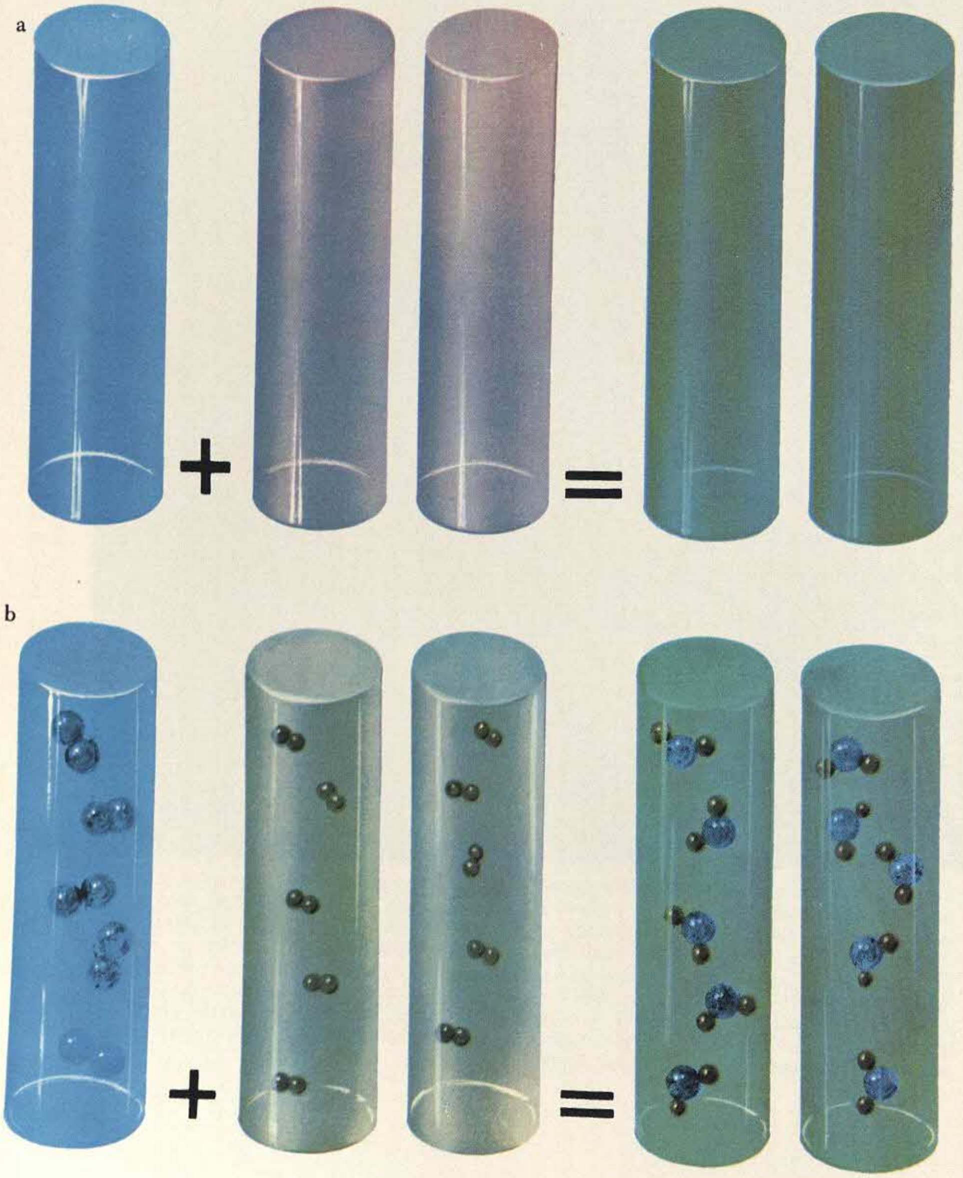
As the nineteenth century dawned, scientists such as the English chemist John Dalton and the French chemist J. L. Gay-Lussac—to mention but two—were taking giant steps in their quest to learn the secrets of matter. Both men made important contributions to the knowledge of gases, but it remained for the Italian physicist Amedeo Avogadro (Illustration 2a) to translate their concepts into numbers.

Avogadro set out to learn how to determine the number of molecules in a certain quantity of matter. The result was a hypothesis stating that under identical conditions, equal volumes of gases contain the same number of molecules. As one writer saw it: "This hypothesis . . . became the very cornerstone of modern chemistry. Every advance after that time in one way or another provided fresh evidence of its truth, so much so that it became customary to refer to Avogadro's *law.*"

The number of molecules in one gram-molecule—or mole (the molecular weight of a substance in grams)—is universally known today as Avogadro's constant, and is represented by the symbol N.

The accompanying illustrations are aids to understanding Avogadro's constant and how its precise value can be determined.

1



A CHARACTERISTIC OF CHEMICAL REACTIONS—Toward the end of the eighteenth century, the English chemist John Dalton concluded that chemical reactions took place between substances that were made up of minute particles, and that these particles combined together in proportions of one and one, or one and two, or one and three, and so forth. This conclusion meant that the old atomic theory first put forward by the Greek philosophers had to be taken up again. This theory was later perfected by means of additions that had been suggested by both experience and the detailed study of how chemical reactions took place. It had been seen that when substances in the gaseous state reacted with each other to form a certain quantity of a final substance, the volumetric proportions of the reacting gases could always be expressed in terms of simple integral numbers. For example, to form water vapor from hydrogen and oxygen requires a reaction between a certain volume of oxygen and twice that volume of hydrogen. The result of this reaction is a volume of water vapor that is exactly double the volume of the oxygen that had been available in the beginning (Illustration 1a). This fact is further clarified by supposing that the gases are composed of identical molecules (Illustration 1b) that combine with each other in the proportions of one and one, one and two, and so forth. In the reaction between oxygen and hydrogen, both the original gases are diatomic (that is, each of their molecules consists of a pair of atoms) and each atom of oxygen combines with two atoms of hydrogen to form a molecule of H_2O. Relatively small molecules such as those of hydrogen, molecules of intermediate dimensions such as those of oxygen, and even larger molecules of water vapor—all occupy the same volume when they are present in equal numbers. Except for the inert gases, all gaseous substances can combine with each other, always obeying this law: equal volumes of different gases under identical conditions of temperature and pressure contain the same number of molecules. This is generally known as Avogadro's law.

AVOGADRO'S CONSTANT—Avogadro's law can be interpreted rather easily by means of a model of the ideal gas. All real gases under standard conditions (standard atmospheric pressure and a temperature of 20° C) possess molecules that are rather distant from one another. The space occupied by ideal molecules (and also by real molecules, which are quite similar to them) is always very small when compared with the total volume of the gas—so it makes no difference if the molecules are large or small.

If an empty receptacle is filled with a certain number of molecules and the whole system is then brought to a certain temperature, the molecules will arrange themselves in a manner that depends on their characteristics and the way in which they move and collide with each other, but not on their individual volumes (Illustrations 2a, 2b, and 2c).

How many molecules may be contained in a given volume of gas? The volume could be a cubic centimeter, a cubic millimeter, or a cubic meter; but it is preferable to adopt another unit of volume when determining the number of molecules it can accommodate. The value of this unit of volume is once again suggested by a chemical fact: with rare exceptions, all elements react with one another in simple proportions (referring to the number of atoms). This makes it desirable to evaluate the weights of the individual elements in such a way that it is easy to evaluate the weights of the compounds obtained from the reactions.

Provided that the chemical reactions are not too complex, observation of the way in which they take place reveals, in practice, the proportions in which the participating atoms combine and the ratio of the weights of the individual atoms. For example, simple weighing shows that 16 g of oxygen combine with 2 g of hydrogen to form 18 g of water. Because it is known that two atoms of hydrogen combine with one atom of oxygen, an atom of oxygen must weigh exactly 16 times more than an atom of hydrogen. (More accurate weighings establish a more exact ratio—16:1.008.)

Combining the elements in all possible ways reveals that hydrogen weighs relatively less than all the other elements—or, conversely, that the others weigh twice as much, three times as much, and so forth, as hydrogen. For chemical purposes, hydrogen is assigned a weight of 1, the basic weight. The weights of other elements are multiples of this unit weight. (In practice, 1/12 of the weight of carbon is used as a unit weight, a fact not germane to this discussion.)

Using the weight of hydrogen as the basic weight makes it convenient to determine how many molecules may be contained in 2 g of hydrogen, in 32 g of oxygen, in 12 g of carbon, or in 238 g of uranium. In elements in the gaseous state, the volume occupied by this number of grams of the substances (within the limits in which gases behave as real gases) will always be 22.414 liters. The number of molecules contained within this volume under standard conditions of temperature and pressure is expressed by Avogadro's constant, represented by the symbol N.

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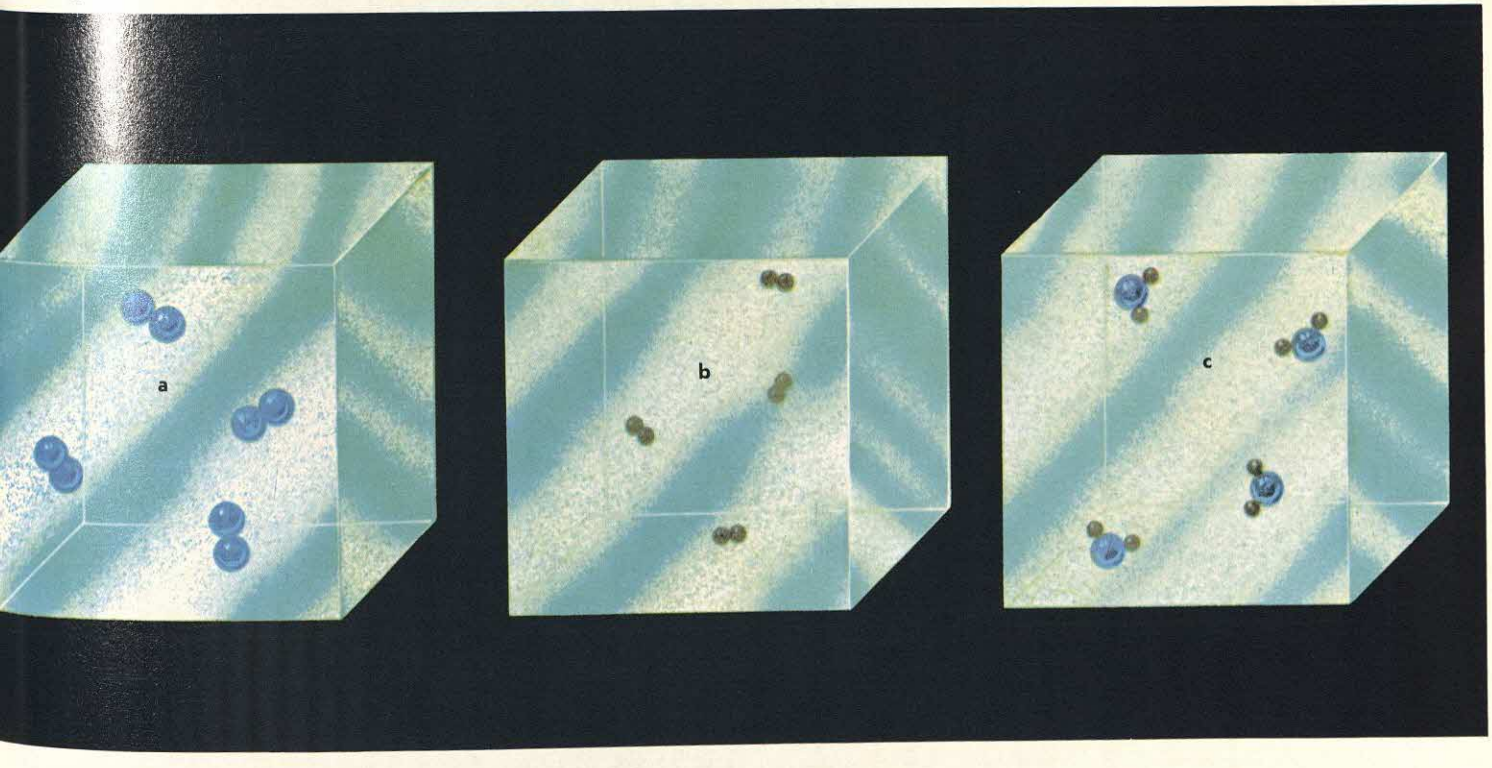

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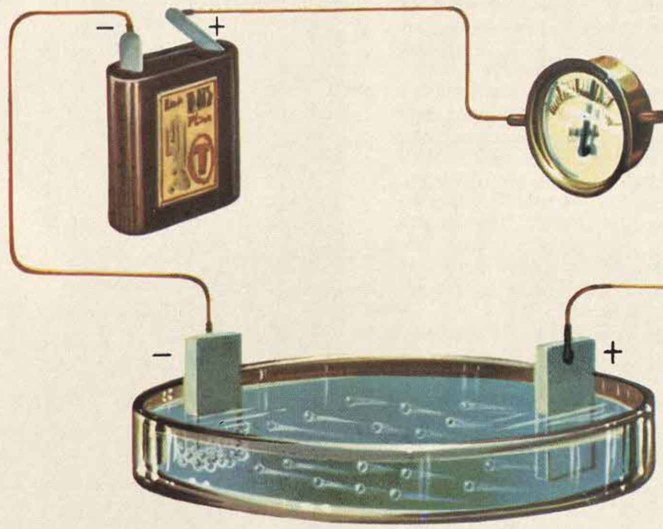
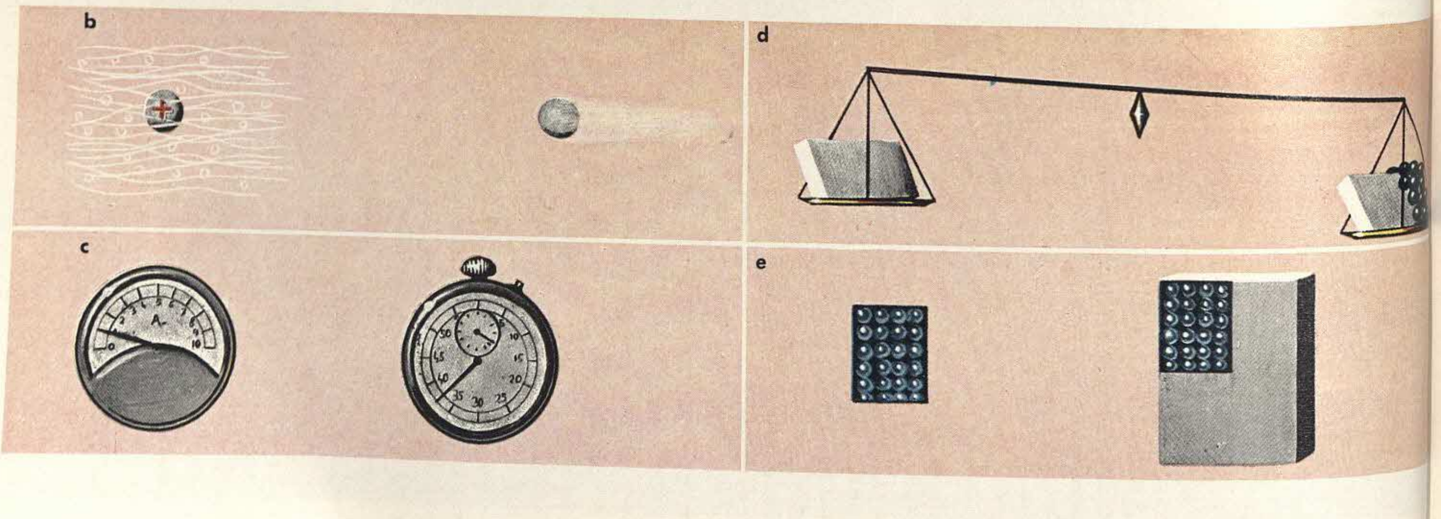


A METHOD FOR DETERMINING AVOGADRO'S CONSTANT—Avogadro's constant is a part of a large number of formulas; hence, if all the quantities other than Avogadro's constant can be measured by any one of these formulas, the constant can be obtained by means of mathematical calculation. There are, therefore, many ways of determining the constant, some of them interesting only from a conceptual or theoretical point of view because they demonstrate how this important physical constant can be calculated by means of the most diverse experiments. Other methods are more important because they enable scientists to determine this constant with great precision. One of the methods that presents no difficulties from the experimental point of view consists of making an accurate measurement of the charge of the electron and involves passing an electric current through solutions of salts (Illustration 3a). A solution of a silver salt (silver nitrate, for example) is placed in a receptacle and two electrodes (two blocks of graphite, for example) are immersed in the solution. When the electrodes are connected to a battery or to some other generator of an electric potential, a current passes through the solution and the silver cations (positively charged ions) in solution collect on the cathode. The silver in the solution is not present in the form of neutral atoms. Because each atom has lost an electron, each atom is a positive ion (cation) that moves toward the negative electrode (cathode). All the electric current passing through the solution is transported by the ions, which migrate slowly toward the cathode. One electron is liberated for every silver ion that migrates toward the cathode (Illustration 3b). The current is allowed to pass for a time; it is then stopped for a measurement of how much current has passed and for how long (Illustration 3c). The product of the current and the time of flow is equal to the charge that has been transported ($q = it$) by the silver atoms. If, for example, a current of 1 A (ampere) has passed for 24,125 sec (slightly more than 6 hours), 24,125 coulombs have passed through the solution. Because 1 coulomb represents the charge of about 6.25×10^{18} electrons, the number of electrons that have passed through the solution is $6.25 \times 10^{18} \times 2.4125 \times 10^4 = 1.51 \times 10^{23}$ electrons. The number of silver ions can be determined easily. The amount of silver that has collected on the electrode weighs about 28 g (Illustration 3d), a quarter of the weight that combines with 1 g of hydrogen or with 8 g of oxygen (Illustration 3e). In fact, two atoms of silver will combine with one atom of oxygen. Therefore, the number determined by the experiment amounts to exactly one fourth of Avogadro's constant N and the value of N must be 6.04×10^{23}. A far more accurate value for Avogadro's constant is used today: 6.02257 (with a likely error of ± 22 on the last two digits) $\times 10^{23}$.

The various methods of determining Avogadro's constant yield different results; nevertheless, it is important to evaluate N by all these methods because some of them yield a value that errs by excess (+ 35, for example) or by defect (− 19, for example). An average value must be obtained by taking into account all the deviations caused by the different experimental methods employed.



DETERMINATION OF AVOGADRO'S CONSTANT

counting atoms one by one

A carpenter finds it relatively simple to cut a board to proper length. He either marks the board as he holds it to the space it is to fit, or he measures the space and transfers the measurement to the board. In either case, he is using a simple, direct, and visual method.

Scientists often cannot rely on such direct measurement. To measure that which they cannot see, they must turn to indirect methods, using more than one means in order to check the results against each other and ensure the greatest accuracy.

Man is not yet able to count the atoms in matter one by one as one might count beans in a bag. They can be counted, however, by various methods that lead ultimately to Avogadro's constant. This constant represents the number of molecules in one gram-molecule—the molecular weight of a substance in grams, called the mole.

The measurement of electrolytic phenomena is one method of determining Avogadro's constant; however, the two most important methods, each completely independent of the other, are based respectively on the measurement of radioactivity and on x-ray diffraction.

THE RADIOACTIVE DISINTEGRATION METHOD

The radioactive disintegration method is important because it is practically the only one that makes it possible to evaluate Avogadro's constant by directly counting the number of atoms.

First, it is necessary to have a certain weight of a radioactive substance—1 gram of radium, for example. The atomic weight of radium can be ascertained by means of chemical experiments, observing the proportions in which radium combines with other substances of known atomic weight. This method shows that the atomic weight of radium is 226, which means that the radium sample is only 1/226 of a gram-atomic weight and that the number of atoms in the sample is equal to 1/226 of Avogadro's constant.

Radium disintegrates because the nuclei of its atoms are not stable. Periodically one of these nuclei emits an alpha particle, a fragment of the nucleus consisting of two protons and two neutrons. Whenever a nucleus undergoes disintegration and violently emits an alpha particle (and possibly other radiation as well), these particles are easily detected by instruments placed around the radium sample. One such instrument particularly suited for detecting the presence of alpha particles is the ionization chamber.

The next step in the radioactive disintegration method is to measure how many particles are emitted by the radium and what weight they have. A sample of radium is placed in an ionization chamber for the purpose of counting the number of particles that are emitted in a unit of time. (In actual practice no ionization chamber would succeed in detecting all the alpha particles that are emitted by 1 g of radium. The measurement is usually carried out on a much smaller quantity —a millionth or a billionth part of a gram, for example—but it is still possible to establish indirectly how many particles 1 g of radium emits in 1 second.)

Every second the 1 g sample of radium gives rise to as many as 3.7×10^{10} atoms of a new element, the noble gas radon. The atomic weight of radon is 222, four mass units less than the atomic weight of radium. To arrive at Avogadro's constant it is necessary to determine what weight of radon is formed in the same time in which a certain number of disintegrations are counted.

The atoms of radon are formed at the same rhythm as that with which the radium atoms disintegrate, which makes it sufficient to measure the disintegration speed of the radium. The radon formed by the disintegration is collected and, after a certain period of time, weighed. This weight is a known fraction of the gram-atomic weight of radon. In a sense, the atoms have been counted one by one, yielding Avogadro's constant. The method described may also be used to determine how many radon particles are emitted in a given time.

In theory the constant can also be determined by weighing the radium, rather than the atoms of radon, and determining how much weight the radium has lost. This method is not practical because radium disintegrates very slowly, making it impossible to determine the loss of weight with sufficient accuracy in a short period of time.

The most practical way of determining Avogadro's constant with the alpha count method involves measuring the volume of helium produced in a certain period of time by a given quantity of radium. The helium is formed by the alpha particles, which acquire two electrons and are transformed into helium atoms. This volume of helium is made up of a number of atoms equal to the number of alpha particles that have been emitted in the particular time period. This number can be easily and accurately calculated if the quantity of radium with which the experiment started, the interval of time, and the number of alpha particles emitted in 1 second by 1 g of radium, are known.

One gram-atomic weight of a monoatomic gas such as helium occupies a volume of 22.414 liters under normal conditions of temperature and pressure. The number of atoms contained in this volume (Avogadro's constant) can be obtained by means of a simple proportion because the number of helium atoms contained in an accurately measured volume has already been determined by the counting procedure previously described.

Measuring the helium formed by the alpha particles is preferable to measuring the radon because radon is radioactive and is subject to further disintegration.

CRITIQUE OF THE EXPERIMENTS

The radioactive disintegration method and the x-ray diffraction method of determining Avogadro's constant both can involve considerable inaccuracies. In measuring the radioactivity it is not always possible to know the exact number of alpha particles that are emitted. The particles often arrive at the counter in pairs, each of which is recorded as one. To avoid this problem would require choosing a radioactive source that emits particles at a slower rate—one that is only very slightly radioactive. However, this would limit the accuracy in weighing the small quantity of material obtained.

The crystallographic method (explained in the accompanying illustrations) has a number of advantages, but is subject to two sources of inaccuracy. First, it is impossible to know the exact wavelength of the x-rays employed. Second, it is difficult to obtain an exact value of the density of the specimen of sodium chloride involved.

THE X-RAY DIFFRACTION METHOD — This method, conceptually as simple as the one based on the measurement of radioactivity, is based on the fact that the atoms in matter are arranged in a regular pattern. If the distances between atoms are known, it is possible to determine how many atoms are contained in a certain volume. Knowing the weight of the volume on which the experiment is being carried out makes it possible to calculate the number of atoms per unit weight. Furthermore, knowing the molecular weight of the substance makes it possible to determine the number of atoms in an amount of the substance whose weight in grams is equal to the molecular weight. The number of atoms in one gram-molecular weight is Avogadro's constant. The experiment is carried out in this way:

The parallelepiped in Illustration 1a is a crystal of rock salt (sodium chloride). Inside the crystal the atoms are arranged at the nodes of a cubic lattice in such a way that atoms of sodium and atoms of chlorine are alternately located along any one line of the lattice. The x-rays make it possible to measure the distances at which the atoms of sodium and the atoms of chlorine are found.

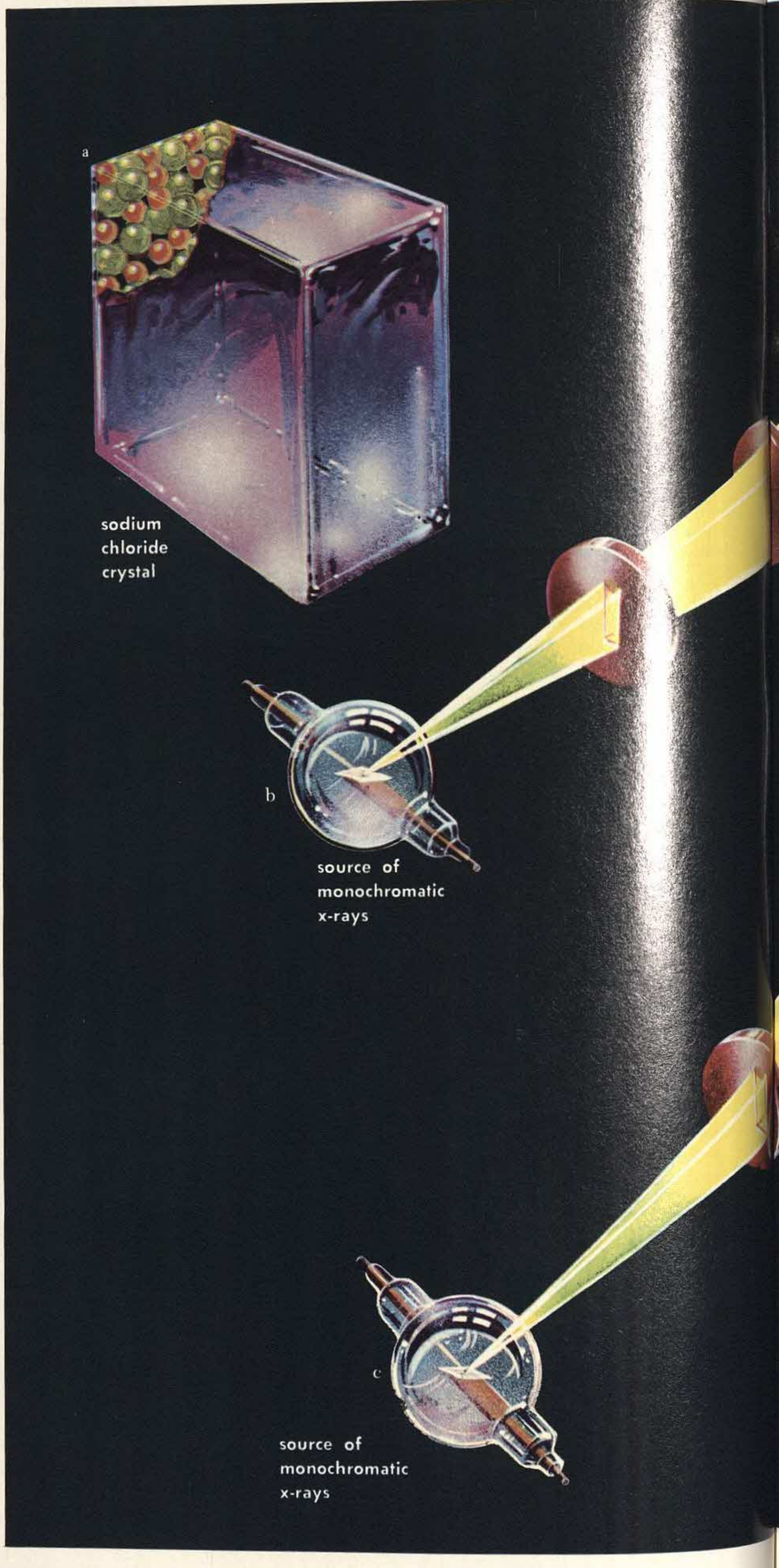
A small cube of rock salt in which the presence of atoms can be seen is shown in Illustration 1b. The cube is illuminated by a thin beam of x-rays, all of the same wavelength; that is, a monochromatic beam that is analogous to a beam of light of a single color. X-rays penetrate matter, and they pass through the cube of rock salt after striking it obliquely. A small part of the beam strikes individual atoms of sodium and chlorine and becomes diffused around them.

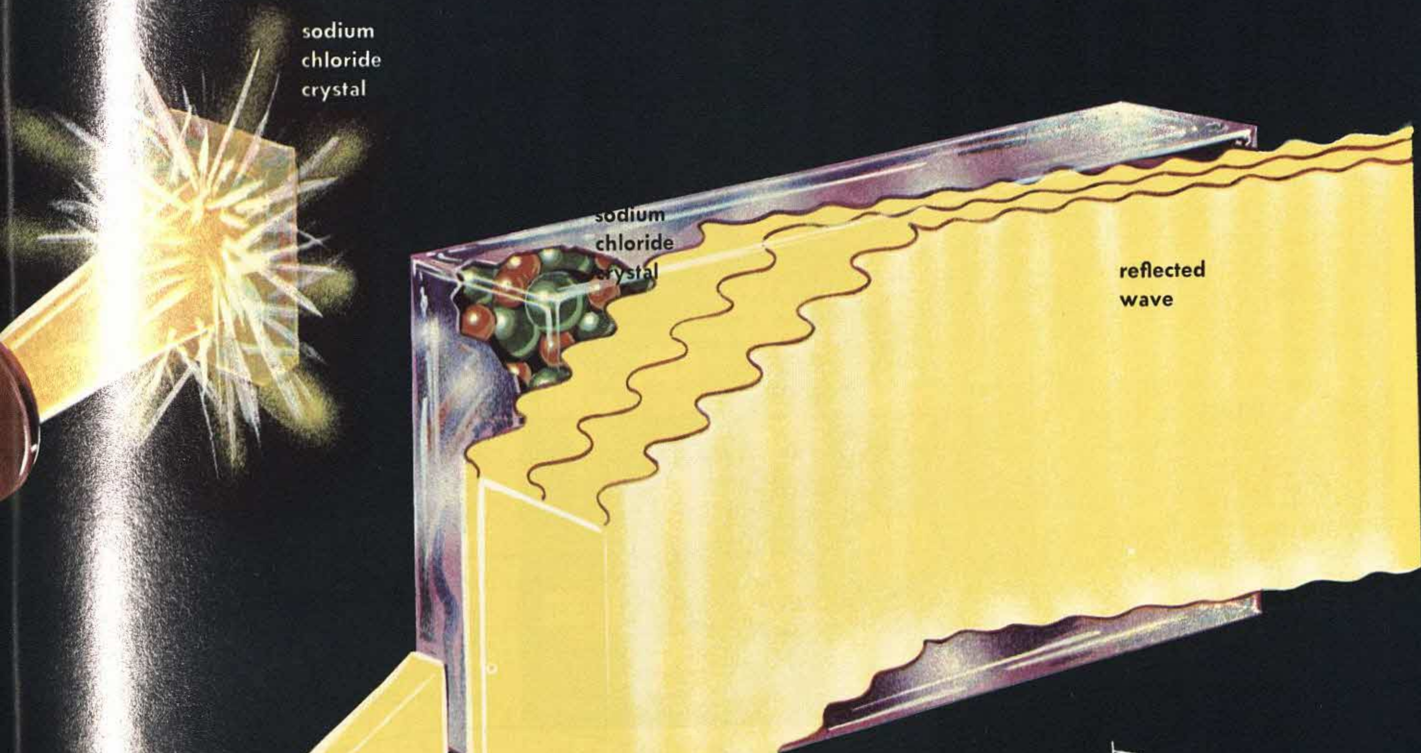
If the x-rays are made to strike a flat face of the cube in such a way that they form a particular angle, the rays will be reflected with a certain intensity. The angle formed by the x-rays and the face of the crystal must be such that the x-rays reflected by a plane of atoms and the plane behind it are forced to travel along two paths whose difference in length is equal to the wavelength of the rays or a multiple of the wavelength. Illustration 1c shows this situation: if the inclination is correct, the waves that emerge from a position near the different layers will be superposed in an additive manner.

As shown in Illustration 1d, the value of the angle at which the phenomenon of the enhanced reflection occurs, α, depends on two characteristics of the experiment: the wavelength of the x-rays λ, and the distance between the layers of atoms **d.** If the wavelength of the x-rays is accurately known, the angle of incidence can be accurately measured by means of a goniometer, which makes it possible to calculate the distance between the planes on which the atoms are arranged in the crystal.

The crystal with a cubic structure (Illustration 1e) has sides that are 1 cm long. Measurement by x-rays shows that the distance between the atoms in rock salt is 2.816 Å (Ångstroms). This means that there are 3.55×10^7 (tens of millions) atoms in one side. The crystal will contain a number of atoms equal to the cube of this number. $(3.55 \times 10^7)^3 = 44.8 \times 10^{21}$ atoms. The weight of a number of molecules of sodium chloride equal to Avogadro's constant is 58.45. The cube of rock salt weighs only 2.165 g and contains exactly 27 times fewer molecules than one mole. Therefore, in one mole of sodium chloride there are $27 \times 44.8 \times 10^{21} = 12.09 \times 10^{23}$ atoms. Because a molecule of rock salt is diatomic—it contains one atom of sodium and one of chlorine—the above number must be divided by two in order to obtain Avogadro's constant. The figure obtained is 6.04×10^{23} atoms.

1


a
sodium chloride crystal
b
source of monochromatic x-rays
c
source of monochromatic x-rays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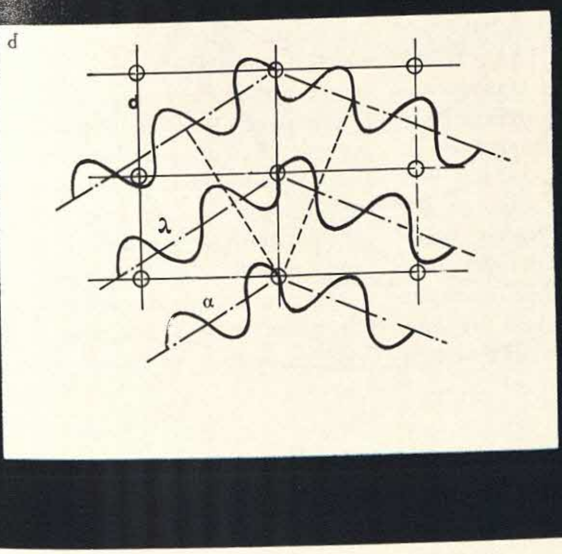
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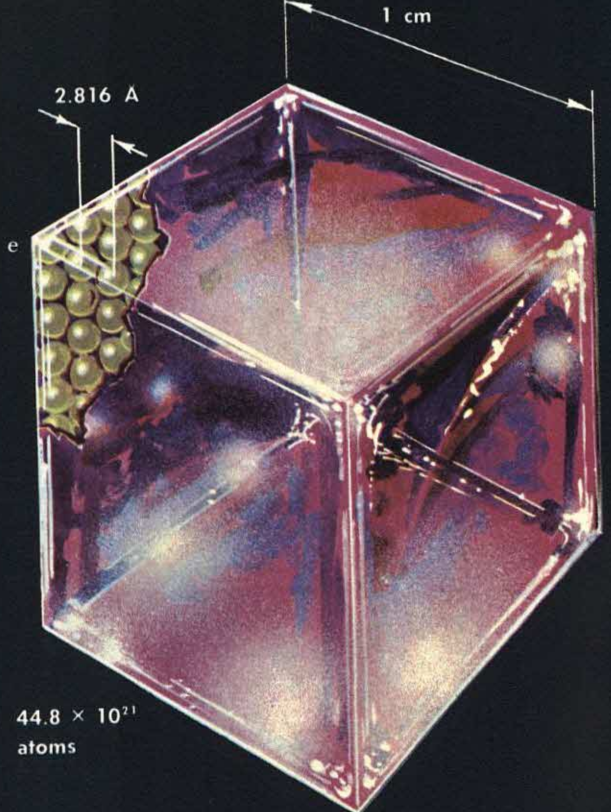

e
2.816 A
1 cm
44.8 × 10²¹
atoms

CHANGES OF STATE | the changes of molecules in changing from solid to liquid to gas

It is interesting to study how matter changes its state, from solid to liquid or gas, from liquid to solid or gas, and from gas to liquid or solid. Examples of these changes are the thawing of ice (solid to liquid), the evaporating of water (liquid to gas), and the condensation of dew (gas to liquid). The questions arise: What causes these changes? What happens to the atoms of a solid, a gas, or a liquid when these changes occur?

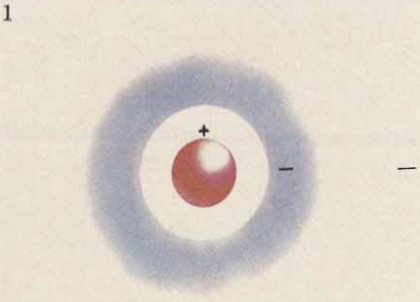
Most substances are composed of molecules comprising atoms of different elements. In order to study what happens to such molecules during a change of state, it is useful first to examine substances that are composed of molecules of a single element. Inasmuch as the changes of state occur in an analogous manner, whether the molecules involved are composed of atoms of a single element or of different elements, it does not limit the study of changes of state if that study is confined to the former kind of molecules, such as those of pure metals—gold, copper, or aluminum—rather than the latter kind of molecules, such as those of water or salt (sodium chloride).

Moreover, in order to understand the phenomenon of changes of state, it is important to review some simple facts about atomic structure—facts that, although extremely important, are not usually well known.

THE STRUCTURE OF THE ATOM

Every atom consists of a heavy nucleus with one or more positive electrical charges in its center and a number of rather light, negatively charged particles (electrons) in orbit around the nucleus. The total structure is somewhat comparable to the sun with its orbiting planets. The number of orbiting electrons is identical to the number of positively charged particles (protons) in the nucleus.

1



THE HYDROGEN ATOM—The hydrogen atom is represented here with the size of the proton deliberately exaggerated. Around the proton, which constitutes the nucleus, is shown a colored cloud; the intensity of the color represents the probability of the activity of the electron at any point within this area.

The simplest of all atoms, that of hydrogen, is shown in Illustration 1; its nucleus has a single positively charged proton around which orbits a single negatively charged electron. Although the structure of an atom cannot be accurately represented by any familiar image (such as that of the solar system), it is useful for the present study to suppose that the hydrogen atom consists of a positively charged central sphere (the nucleus), surrounded by a sphere in which the negatively charged electron moves.

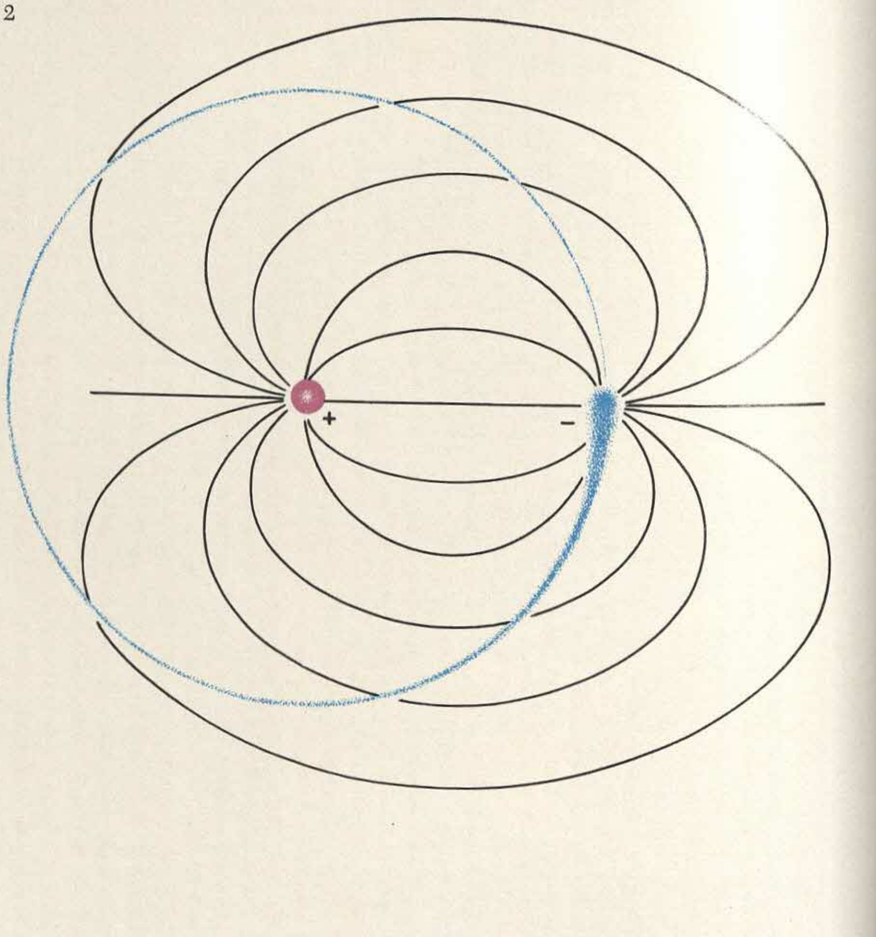
When seen from outside and at a distance, the atom would appear to be a single, neutral entity, without electrical charge. Actually, however, it contains, in exact balance, both positive and negative charges.

ATTRACTIVE FORCE WITHIN THE ATOM

In Illustration 2, the nucleus and the electron of a hydrogen atom are represented as linked by lines that indicate lines of force. If a charged particle were to appear at any point along one of these lines, it would be subject to force acting in the direction of the line on which it appeared, that is, in the direction of either the nucleus or the electron—for all the lines of force pass between the nucleus and the electron.

THE ELECTRIC FIELD OF THE HYDROGEN ATOM—The electric field between two oppositely charged particles exercises a force on any other charged particle that may appear between them; this force always acts in the direction of the lines of force that join the two particles, such as the proton and electron of the hydrogen atom. Even though the combined effect of these charges produces a neutral atom, under certain conditions the atom can exercise electrical forces (of this type) on charges outside the atom.

2

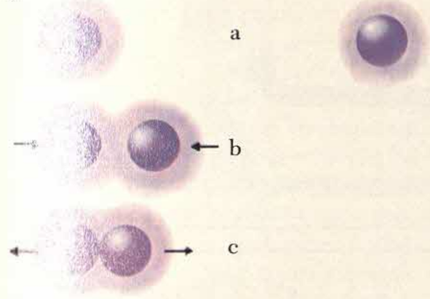


The blue circle represents the orbit of the electron around the nucleus. The electrostatic attraction exercised beyond this orbit by the atomic particles is negligible, but within the space defined by this orbit the attraction is strong. Penetration of the space within the orbit destroys the structure of the atom.

ATTRACTIVE FORCE BETWEEN ATOMS

If two atoms are at a great distance from each other, no measurable force is exercised between them (Illustration 3a). (In this context, a great distance must be understood as relative to the diameter of the orbit of the outermost electron of each atom.) However, if the distance between the two atoms is only slightly greater than the diameters of the outermost electron orbits, the atoms will exercise a weak electrostatic attraction on each other (Illustration 3b).

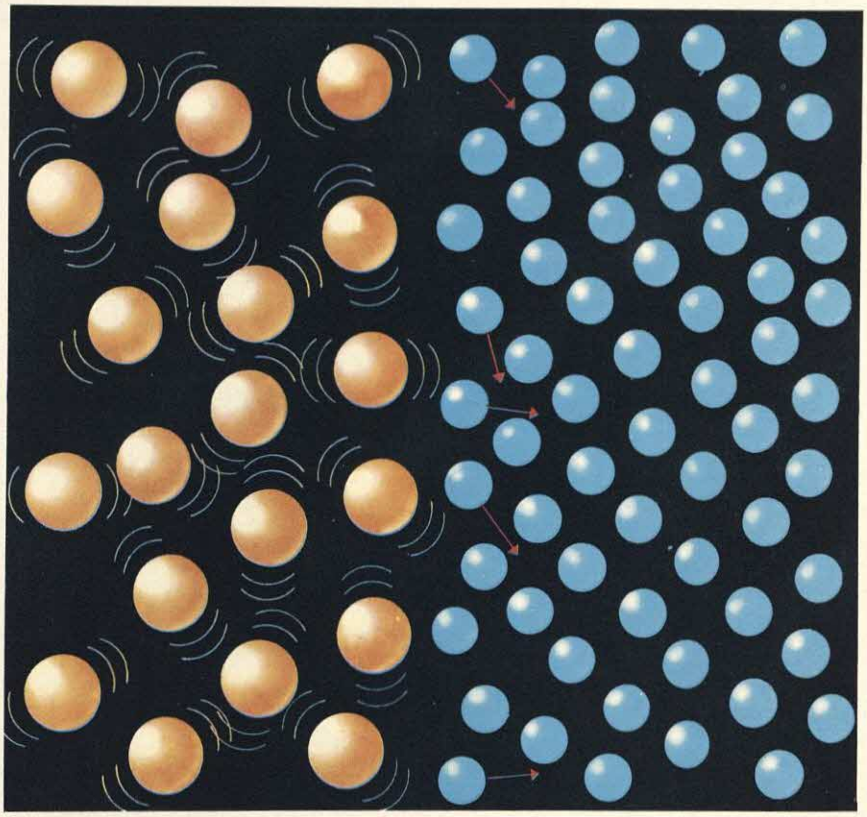
3



THE ATTRACTION BETWEEN ATOMS—No measurable force is exercised between two atoms that are far apart (Illustration 3a). Two atoms that are near each other attract each other (Illustration 3b). Two atoms that are contiguous repel each other (Illustration 3c).

Furthermore, if the two atoms are brought still closer together so that the spacing between them is less than one diameter (Illustration 3c), their outermost electrons will be forced to make changes in their orbits and to follow paths that are neither circulár nor elliptical—but distorted. This change in orbits will result in a repulsion between the two atoms, and that repulsive force will exceed the attractive force that existed before the atoms were moved into close proximity.

4



THE HEATING OF A LIQUID—The illustration shows the atoms of a liquid (on the right) coming in contact with the atoms of the container (left). The container is hot; therefore, its atoms are agitated and vibrate within their fixed positions. Those in contact with the atoms of the liquid accelerate the latter and agitate them. This at first affects only the atoms in direct contact with the atoms of the container; but the agitation spreads among the atoms of the liquid, and eventually all the atoms have the same energy, at which point the liquid becomes uniformly heated.

THE EFFECT OF HEAT

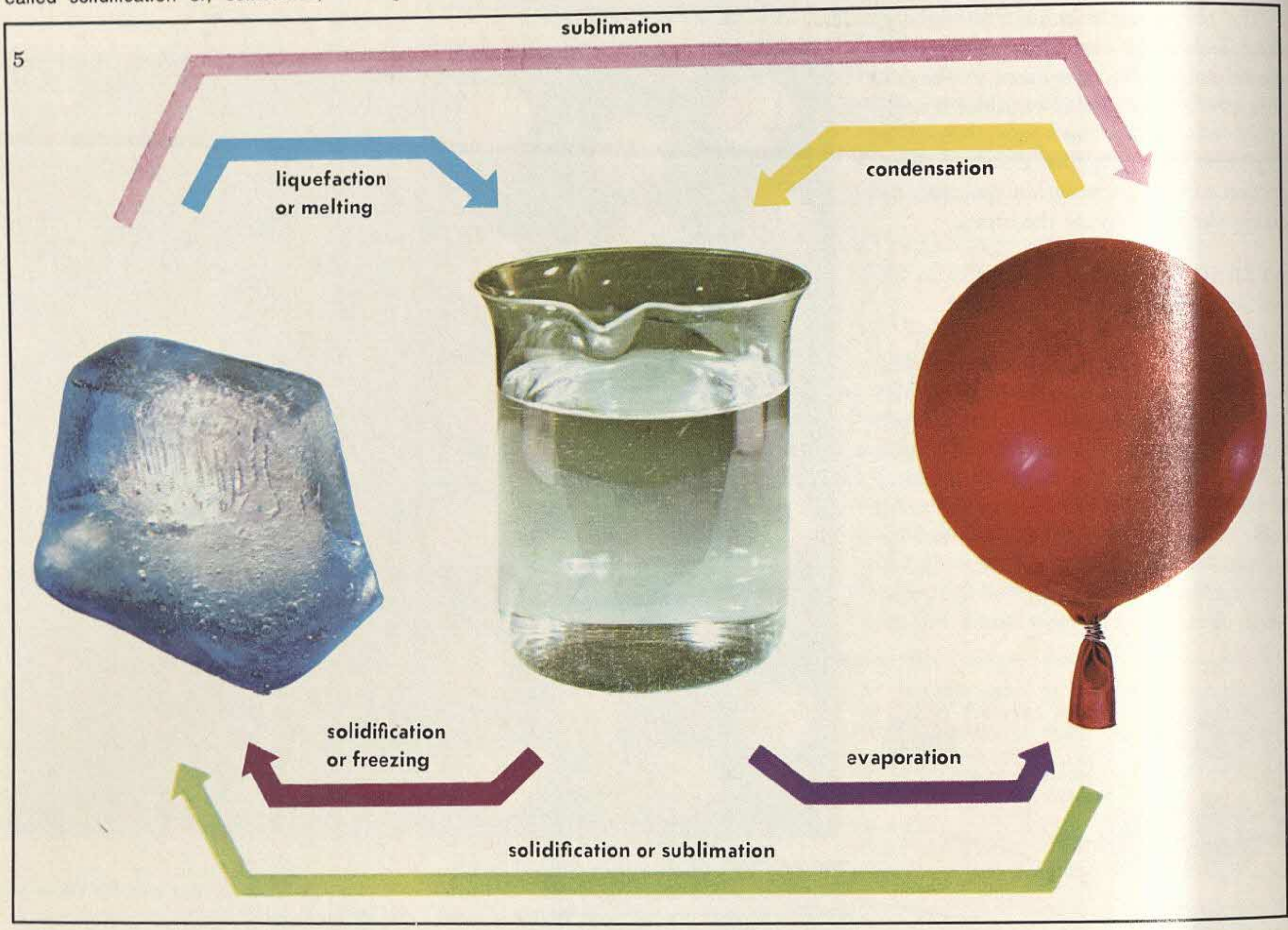
An increased movement of atoms results in the phenomenon of heat. Illustration 4 shows the arrangement of atoms in a liquid (the spheres on the right) that has just been placed in a container (those on the left). The container is hot and the liquid is cold. The atoms of the container are strongly agitated; although they always occupy a fixed position in relation to one another, they vibrate in that position and collide with one another in doing so. Each atom possesses about the same amount of energy, depending on the temperature of the container. As for the atoms of the liquid in the container, they are also agitated, but less so than those of the container itself.

However, when the atoms of the liquid come in contact with those of the container, the former are accelerated by impact with the latter, and their agitation increases. The first atoms so affected will be the liquid atoms in direct contact with the container atoms. The agitated liquid atoms will then collide with nearby atoms in the liquid and transmit the energy received from the container atoms. The agitation will spread, as heat, among the atoms of the remainder of the liquid, until all of these have the same amount of energy as the container atoms.

When considering an object that is being heated, it must be understood that its atoms are undergoing an increasing speed of agitation; the hotter the object, the more rapid the motion of its atoms. To

THE CHANGES OF STATE—The change from solid to liquid is called liquefaction or melting. The reverse change, from liquid to solid, is called solidification or, sometimes, freezing. The change from liquid to gas is called evaporation, and the reverse process is called condensation. It is possible for a solid to change to a gas without melting; this is known as sublimation. The reverse process, from gas to solid, also occurs and may be called either solidification or sublimation.

5



increase the speed of motion of the atoms, the object is placed in contact with another object with more agitated atoms.

The understanding of these facts makes it possible to discuss the phenomenon of changes of state.

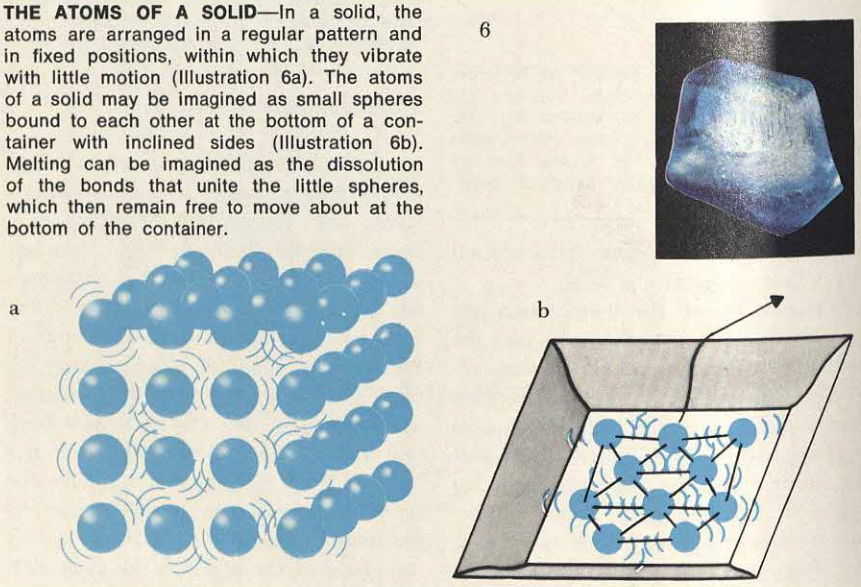
MELTING OF SOLIDS

Melting is best understood by examining the structure of a solid and the arrangement of its atoms.

Each atom of a solid is in a fixed position, capable of moving only by vibrating within that position (Illustration 6a). The atoms cannot move from this fixed position because they are contiguous to each other and are, therefore, subject to forces operative at such short range. An atom in the center of the group depicted here is attracted with equal force to each of the atoms surrounding it. But an atom on the surface of this group, although bound by the force of all the atoms contiguous to it, is not surrounded by atoms on all sides. If energy is applied, such an atom may be detached from the forces that bind it on all the other sides.

THE ATOMS OF A SOLID—In a solid, the atoms are arranged in a regular pattern and in fixed positions, within which they vibrate with little motion (Illustration 6a). The atoms of a solid may be imagined as small spheres bound to each other at the bottom of a container with inclined sides (Illustration 6b). Melting can be imagined as the dissolution of the bonds that unite the little spheres, which then remain free to move about at the bottom of the container.

6



This is precisely what is involved in the melting or liquefaction of a solid. It must be heated; that is, the atoms that compose it must be subjected to additional energy so that they may be agitated at greater speed. But each atom at the surface must be detached, and enough energy must be supplied to perform the work involved in detaching the surface atoms.

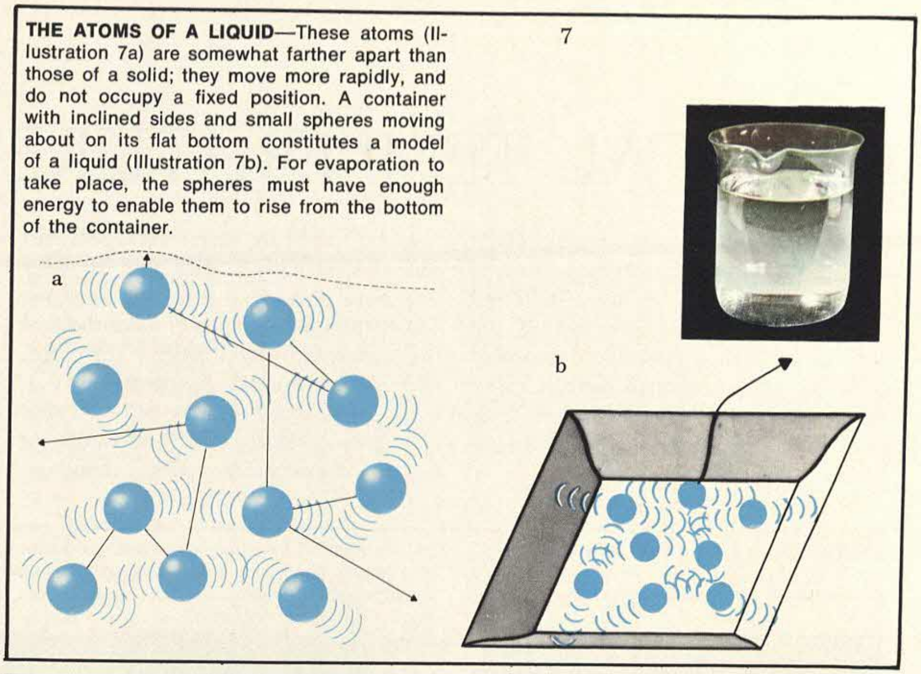
Thus melting or liquefaction can be represented (Illustration 6b) as increased agitation of the atoms, enabling them to break the bonds that fix them in the structure and thus to release them.

EVAPORATION OF LIQUIDS

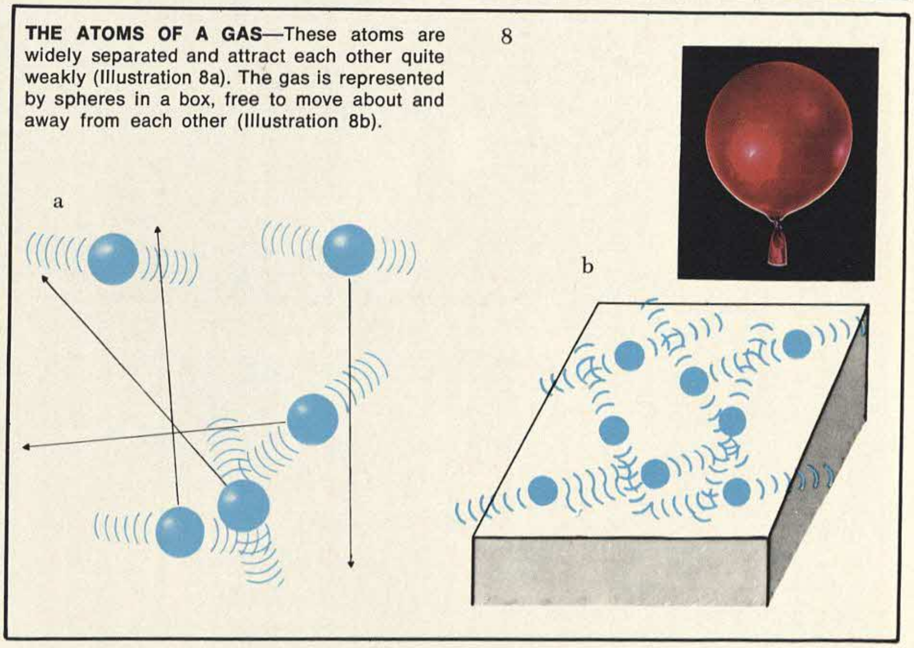
The atoms of a liquid (Illustration 7a) move with greater speed than those of a solid and do not occupy a fixed position. They are still influenced by the forces of attraction that atoms exert on each other, but these forces are weaker in a liquid than in a solid because the atoms of a solid are farther apart. The forces are strong enough to maintain a constant volume, but not strong enough to fix the shape of the volume. The shape is determined by the container—the atoms making up the liquid are pulled to the lower portion of the container by gravity. The atoms close to the surface are bound by forces that attract them toward the interior, much like those of a solid.

Evaporation—changing from the liquid to the gaseous state—results when atoms are detached from the surface of the liquid, a process that requires the application of energy to the liquid.

In the liquid represented in Illustration 7b, the distance between the atoms is fairly small; they maintain this average distance as they move about, but each atom can reach any point within the container until it receives sufficient energy to rise to the surface and cross the rim. If a gas is cooled, its atoms are slowed down; this results in condensation—changing from the gaseous to the liquid state, the reverse of evaporation. If the atoms of the gas move about slowly, they tend, in approaching each other, to become subject to the short-range forces of attraction between atoms. The result is the formation of a drop of liquid that attracts nearby atoms and increases in size at the expense of the volume of gas, which, of course, decreases.



THE ATOMS OF A LIQUID—These atoms (Illustration 7a) are somewhat farther apart than those of a solid; they move more rapidly, and do not occupy a fixed position. A container with inclined sides and small spheres moving about on its flat bottom constitutes a model of a liquid (Illustration 7b). For evaporation to take place, the spheres must have enough energy to enable them to rise from the bottom of the container.



THE ATOMS OF A GAS—These atoms are widely separated and attract each other quite weakly (Illustration 8a). The gas is represented by spheres in a box, free to move about and away from each other (Illustration 8b).

CONDENSATION AND SUBLIMATION OF GASES

The average distance between the atoms of a gas is great enough to ensure that their reciprocal attractions are weaker than the forces of repulsion that result from their collisions. Therefore, they tend to move as far as possible from each other, and the volume of the gas is not confined by any obstacle to its expansion (Illustration 8a) except the walls of the container. The atoms are still affected by gravity, but they are moving so rapidly that they do not have an opportunity to collect in the lower portion of the container, as do the atoms in a liquid. A gas may be represented by a group of spheres in a box (Illustration 8b). The atoms are free to move about within the box and to move away from each other unhindered; the walls of the box, however, which correspond to the walls of a container, keep the atoms confined.

In order for a gas to condense into a liquid or to sublime into a solid, the atoms must first be slowed down to such an extent that, when they approach one another and collide, the attractive forces exercised between atoms at short range will either keep them at the distance characteristic of a liquid or at the distance and in the fixed position characteristic of a solid.

THE TEMPERATURES OF CHANGE

The temperatures at which changes of state occur depend on the velocities that the atoms (and the molecules) must attain in order to be able to detach themselves from the structures they form, or to which they must be slowed down in order to become bound together to form such structures. These temperatures, which depend on the mass of the atoms themselves and on the forces they exercise on each other, indicate the intensity of the bonds between the atoms and, therefore, their capacity to remain bound together, whether as gases, liquids, or solids.

Changes of state occur in a precipitous fashion as temperature is varied. For example, if H_2O is at −0.01° C, slightly below the "transition temperature," it is ice. If the temperature is raised slightly, to 0.01° C, a totally different state results —water. The exact mechanism by which this change of state takes place still puzzles scientists today.

CRITICAL TEMPERATURE | the frontier between two states

Early nineteenth-century scientists could convert most gases into liquid form by compressing them, but they could not understand why some gases did not liquefy even when subjected to enormous pressure. These seemingly defiant gases, called incompressible or permanent, include such important ones as hydrogen, oxygen, nitrogen, and helium.

Around 1880 the Irish chemist Thomas Andrews was able to show that for gases in general there is a temperature above which they do not liquefy, regardless of the pressure to which they are subjected. This is the critical temperature (T_c), above which any substance will exist only in a gaseous state, and each substance has its characteristic critical temperature. As most gases are compressed or cooled, their molecules move closer together. The intermolecular forces of attraction change the random arrangement of the gas molecules to the more orderly arrangement of the molecules in a liquid. Thus, the critical temperature of a substance depends upon the degree of attraction between its molecules.

STEAM JET—An example of a gas turning into liquid at less than critical pressure is steam, which condenses into droplets of water on any surface that has a temperature lower than that of the steam. But some gases, called incompressible gases, do not liquefy even when subjected to very high pressures. A high-pressure steam jet is shown.

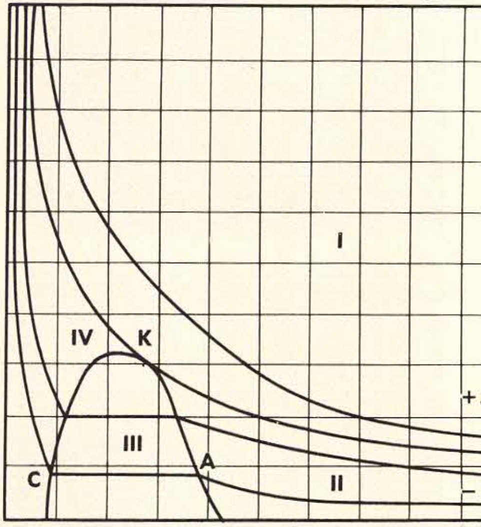
1

Water is a polar substance having extremely strong forces of attraction between its molecules. It can remain liquid at temperatures up to 374° C (about 705° F), a very high critical temperature. In helium the forces of molecular attraction are very weak. Helium must be cooled to −267.9° C (about −450° F) to liquefy. At that low temperature the molecules are moving extremely slowly, and a pressure of only 2.26 atmospheres (critical pressure) will liquefy helium.

Illustration 3 shows the behavior of carbon dioxide, CO_2, when temperature is constant, and pressure and volume vary. The graph shows a series of curves along which the temperature remains unchanged; these are isothermic curves, or isotherms. The lowermost curve shows a temperature of −18.1° C (about 0° F). Beginning from the right, where the values for volume are high, the curve rises slowly because small increases in pressure are sufficient to cause large contractions in volume. At point A, although volume continues to diminish, pressure remains constant and the curve becomes a straight line and perfectly horizontal. Carbon dioxide begins to liquefy at point A and is liquefied completely at point C. From this point on, because only liquid is present, small contractions in volume mean enormous increases in pressure, a characteristic typical of liquids that are extremely hard to compress. The curve then seems to rise almost parallel to the vertical axis. The isotherms, which represent changes in volume and pressure, for higher temperatures will behave in a similar way, even if the horizontal stretch of the curve becomes shorter.

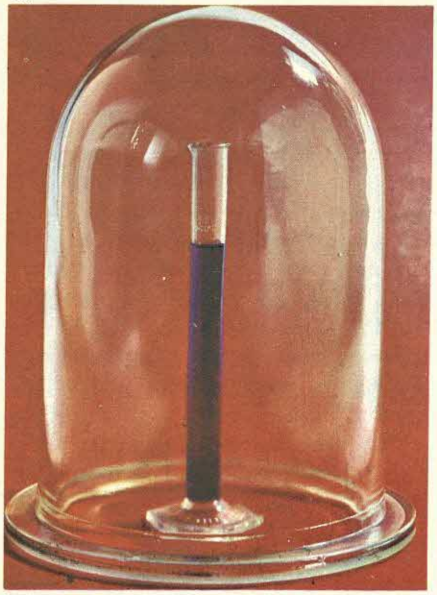
In Illustration 3, the isotherm of 31.1° C (about 88° F) has a horizontal stretch reduced to a single point, K. Point K is the critical point, which is the point of critical temperature, critical pressure, and critical volume. At temperatures above 31.1° C, it is no longer possible to liquefy carbon dioxide. Higher isotherms show that the curve never becomes horizontal, but tends toward the shape of curves for ideal gases as set forth in Boyle's law. Joining the points representing the beginning and end of liquefaction produces an Andrews curve that divides the graph into four areas, each representing a different state of carbon dioxide. The first area (I), above the critical 31.1° isotherm, represents the carbon dioxide that does not become liq-

3

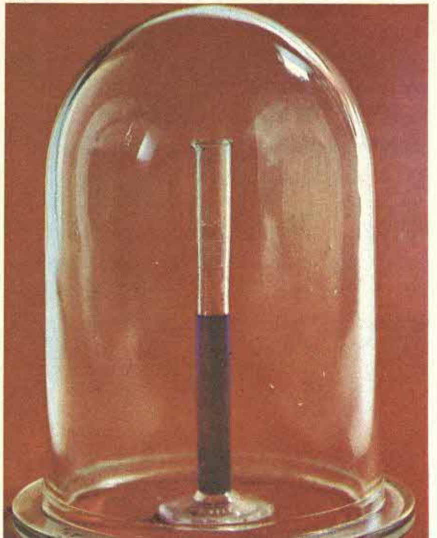


ANDREWS CURVE—This graph shows the behavior of carbon dioxide when pressure and volume are varied at specific constant temperatures. The two lowermost curves include a rectilinear stretch between the point where liquefaction begins and the point where liquefaction is complete. (On the isotherm of 31.1° C, this stretch is reduced to the single point, K.) The curve joining all the points at the beginning and end of liquefaction forms the Andrews curve. The space enclosed by the Andrews curve (area III) represents saturated vapor, the gas with its liquid.

4a



4b

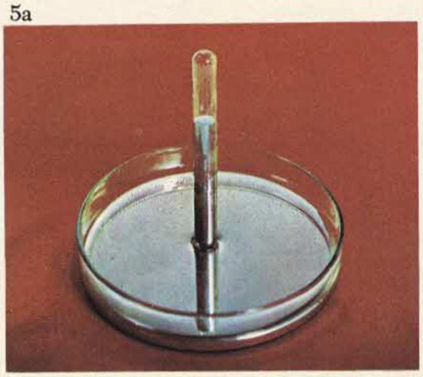


VAPOR TENSION—A cylinder containing liquid chloroform has been placed under a bell-shaped glass cover (Illustration 4a). The level of the chloroform falls (Illustration 4b) because molecules have passed from the liquid into the surrounding space, saturating the space. The molecules present as gas exert a pressure that is called vapor pressure.

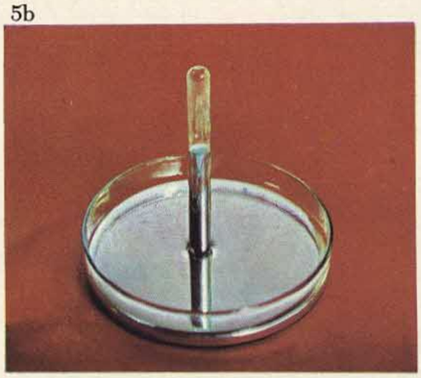
LIQUID NITROGEN—Liquid nitrogen is being poured from its container. Nitrogen is a gas that liquefies at −180° C (−292° F).

2

5a

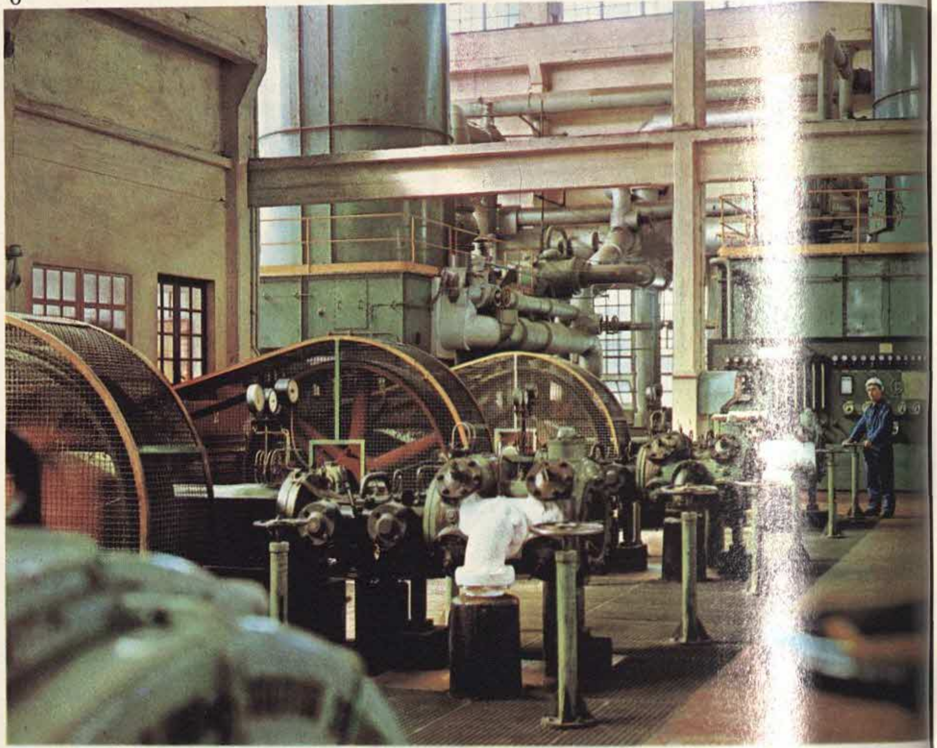


5b



VAPORIZATION IN A VACUUM—An ordinary barometer is the simplest instrument for measuring vapor tension (see below).

6



LINDE MACHINES—A Linde machine, shown here in a large industrial complex, is most commonly used to liquefy air. Developed in 1874 by the German engineer, Carl von Linde, this method is still used in modern research into the physics of low temperatures.

uid and is a gas. The second area (II), whose upper boundary is the critical isotherm and the righthand branch of the Andrews curve, represents unsaturated gas that can be liquefied by compression. The third area (III), enclosed by the Andrews curve, represents saturated gas. The fourth area (IV) represents liquid carbon dioxide.

Along the horizontal stretch of the isotherm between A and C the carbon dioxide exists in both gaseous and liquid state. Because the line AC is parallel to the axis showing volume, pressure is constant and the gas and liquid are present independently of their relative proportions. The pressure of a gas when it coexists with its liquid is called the vapor pressure of the liquid at a given temperature. Illustration 4 shows a cylinder containing liquid chloroform under a bell-shaped glass cover. The level of the choloroform will drop because the liquid contains molecules with enough kinetic energy to escape and to vaporize. The first move, therefore, is from the liquid to the surrounding space. Because the space is not very large, any increase in the concentration of molecules escaping from the liquid means an increase in the probability that the liquid will reabsorb some of them. At some moment, the rate at which the molecules are escaping from the liquid will be equal to the rate at which they are being reabsorbed. Although there is no visible indication of it, the system is not at rest because molecules are moving continually in both directions. The equilibrium is dynamic rather than static.

The molecules present in the gaseous phase clearly exert some pressure, which is the vapor pressure. This pressure varies according to the temperature and the nature of the liquid. Increasing the temperature of a liquid increases the average kinetic energy of the molecules and increases the number of molecules that reach a threshold of energy high enough to cause them to escape from the liquid and to vaporize. When the temperature rises, the vapor pressure rises.

The nature of a liquid has considerable bearing on its vapor pressure. In water, the forces of molecular attraction are so strong that it is difficult for the molecules to escape; the vapor pressure is low. In liquids such as chloroform, the forces of molecular attraction are very weak, and a large number of molecules escape into gas; the vapor pressure is high.

An ordinary mercury barometer (Illustration 5a) can be used to measure vapor pressure. A glass tube with one end closed is filled with mercury, then turned upside down in a small pan also filled with mercury. The mercury in the tube falls, and the distance it falls reflects the atmospheric pressure. Above the mercury in the tube is a vacuum. A few drops of another liquid are introduced into the tube from below. Because most liquids are lighter than mercury, the liquid rises as far as the vacuum, and there the liquid evaporates, causing the vapor in the vacuum to become saturated. This exerts pressure on the column of mercury, causing the column to fall in proportion to the force exerted on it. The distance that the mercury column falls reflects the vapor pressure of the liquid at the temperature at which it was measured (see Illustration 5b).

BOILING AND FREEZING POINTS

properties that characterize substances

A watched pot may ultimately boil, but the nature and purity of the liquid within the vessel will determine how long one must wait before the liquid is ready to use.

By comparing the boiling or freezing points of tap water with the boiling and freezing points of pure water, the degree of purity and corresponding molecular weight of the tap water can be determined. This method of determination holds true for all substances.

When a foreign substance (a solute) is added to a pure liquid (a solvent), the boiling point of the solution will be higher than that of the solvent. Conversely, the mixture's freezing point will be lower. These physical changes form the basis of the ebullioscopic and cryoscopic methods (respectively) for determining the molecular weight of a liquid. When utilizing the ebullioscopic method, the equation used in calculating the molecular weight of a solvent is

$$M_2 = K_e \frac{1000}{\Delta T} \frac{G_2}{G_1} \qquad (1)$$

where M_2 is the solution's unknown molecular weight, K_e the characteristic of the solvent (generally known as the ebullioscopic constant), and G_1 and G_2 the respective weights (in grams) of the solvent and solute. ΔT is the measured increase in the boiling point of the solution over and above that of the pure solvent.

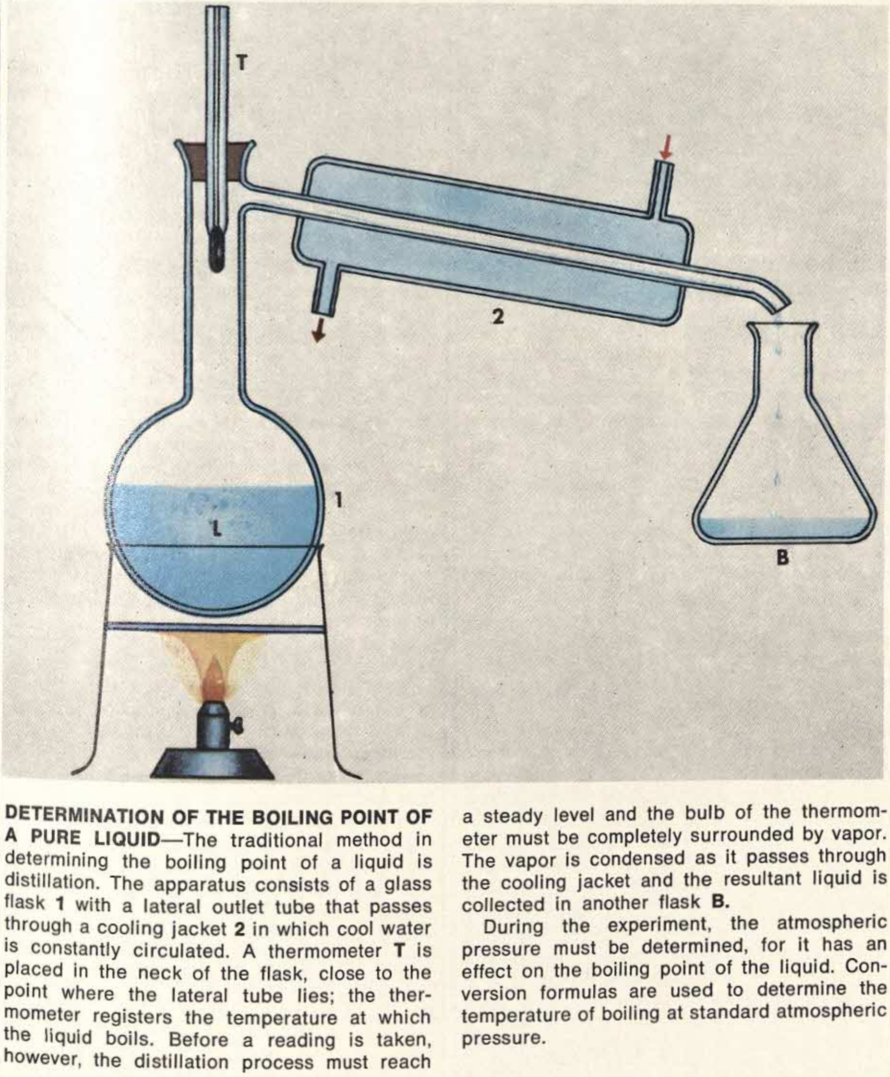
The equation used in the cryoscopic method is analogous to equation (1). Its form is

$$M_2 = K_c \frac{1000}{\Delta T} \frac{G_2}{G_1} \qquad (2)$$

where ΔT represents the lowering of the freezing point. K_c is another characteristic of the solvent—the crysocopic constant.

The table below shows the constants K_e and K_c for water and some other liquids. Equations (1) and (2) are valid only when the solution is a highly diluted one. The equations have an alternate use: if the solution consists of two substances with known molecular weights, their proportions can be determined.

1



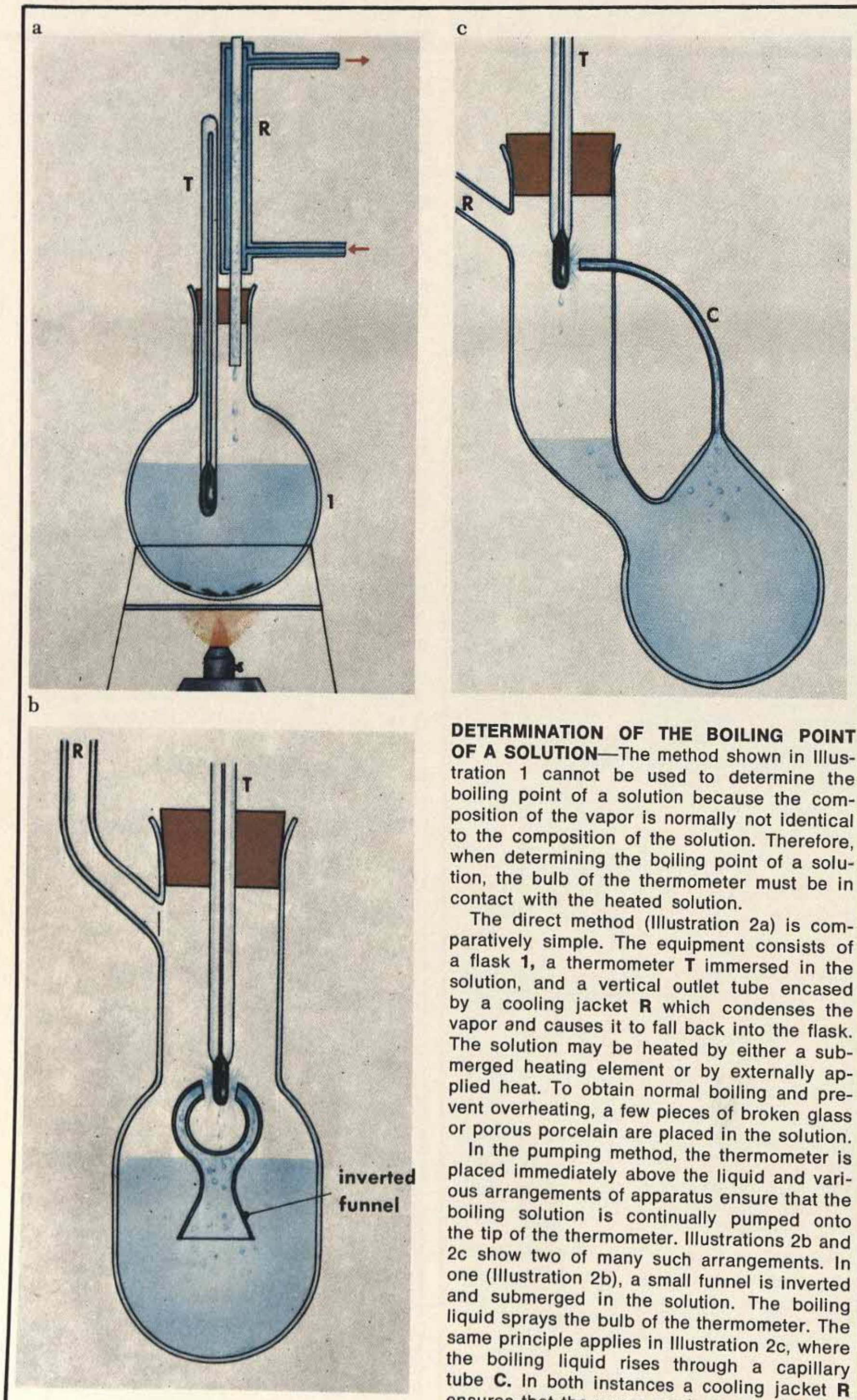
DETERMINATION OF THE BOILING POINT OF A PURE LIQUID—The traditional method in determining the boiling point of a liquid is distillation. The apparatus consists of a glass flask **1** with a lateral outlet tube that passes through a cooling jacket **2** in which cool water is constantly circulated. A thermometer **T** is placed in the neck of the flask, close to the point where the lateral tube lies; the thermometer registers the temperature at which the liquid boils. Before a reading is taken, however, the distillation process must reach a steady level and the bulb of the thermometer must be completely surrounded by vapor. The vapor is condensed as it passes through the cooling jacket and the resultant liquid is collected in another flask **B**.

During the experiment, the atmospheric pressure must be determined, for it has an effect on the boiling point of the liquid. Conversion formulas are used to determine the temperature of boiling at standard atmospheric pressure.

EBULLIOSCOPIC AND CRYOSCOPIC CONSTANTS OF SOME LIQUIDS

Substance	K_e	K_c
acetic acid	3.9	3.08
acetone	1.7	2.4
aniline	5.87	3.22
benzene	2.7	5.1
benzoic acid	8.32	–
camphor	6.0	40.0
carbon disulfide	3.8	2.37
carbon tetrachloride	5.0	30.0
chloroform	3.8	4.9
cyclohexane	20.2	2.79
ether	2.2	1.8
naphthalene	–	7.0
nitrobenzene	7.0	5.26
phenol	7.27	3.04
pyridine	4.97	–
water	0.52	1.86

2

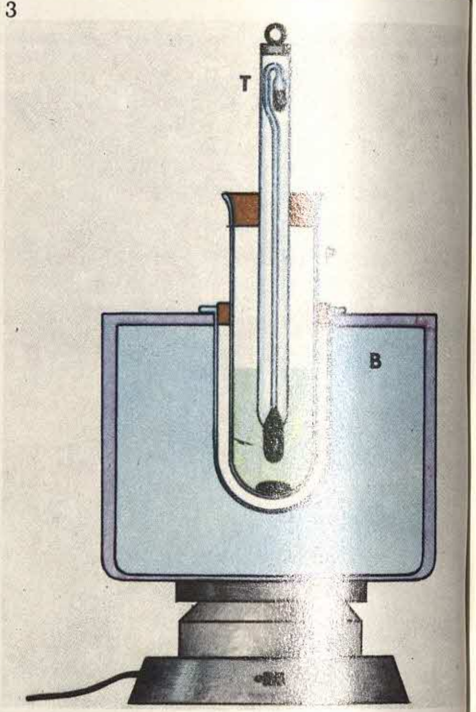


DETERMINATION OF THE BOILING POINT OF A SOLUTION—The method shown in Illustration 1 cannot be used to determine the boiling point of a solution because the composition of the vapor is normally not identical to the composition of the solution. Therefore, when determining the boiling point of a solution, the bulb of the thermometer must be in contact with the heated solution.

The direct method (Illustration 2a) is comparatively simple. The equipment consists of a flask **1**, a thermometer **T** immersed in the solution, and a vertical outlet tube encased by a cooling jacket **R** which condenses the vapor and causes it to fall back into the flask. The solution may be heated by either a submerged heating element or by externally applied heat. To obtain normal boiling and prevent overheating, a few pieces of broken glass or porous porcelain are placed in the solution.

In the pumping method, the thermometer is placed immediately above the liquid and various arrangements of apparatus ensure that the boiling solution is continually pumped onto the tip of the thermometer. Illustrations 2b and 2c show two of many such arrangements. In one (Illustration 2b), a small funnel is inverted and submerged in the solution. The boiling liquid sprays the bulb of the thermometer. The same principle applies in Illustration 2c, where the boiling liquid rises through a capillary tube **C.** In both instances a cooling jacket **R** ensures that the vapor condenses and returns to the flask.

3



CRYOSCOPIC MEASUREMENTS—Almost all equipment used to determine freezing points, or the lowering of such points, is designed after the classic apparatus constructed in 1888 by the German physicist H. Beckmann. The integral part of the apparatus is a special thermometer—known as the Beckmann thermometer—that measures temperature differences of about 5-6 C° to an accuracy of one-thousandth of a degree. The thermometer **T** is fixed inside a large test tube **P** and is immersed in the liquid. An air jacket prevents excessively rapid heat exchanges between the test tube and the thermostatically controlled water bath **B.** A magnetic agitator at the bottom of the test tube circulates the liquid and ensures even heat distribution.

When taking a measurement, the thermostat is set about 4° C below the expected freezing point of the solution, which will then be cooled at a slow rate. During the cooling process, care must be taken to assure that the agitator functions properly. When the freezing point is reached, small crystals separate from the solution and the temperature remains constant.

When no crystallization occurs at the freezing point and the temperature continues to fall, supercooling may occur. In such a situation, the system may be further agitated, or a small crystal of the solid that will be formed during the experiment may be added to provoke crystallization. The temperature will then rise and eventually stabilize at the correct freezing point.

SUBLIMATION, FUSION, AND EVAPORATION

the changes of state

Of all the wonders of childhood, perhaps the most continually entrancing is the way various things "change into something else." In fact, a good deal of every child's "Why?" is rooted in the never-ending human quest to discover nature's secrets. So, early in life the child sees water boil away into steam, gravy congeal as it cools, butter melt in a hot pan. Invariably, he asks, "Why? What makes it do that?"

Physics has many of the answers to these so-called phase changes, or changes of state of aggregation. Actually, the three fundamental states of matter–solid, liquid, and gas–are not irreversibly defined. However, changes from one state to another obviously can and do occur with changes in temperature and pressure. The terms used to indicate the various changes are: (1) *fusion*, for change from the solid to the liquid state (with solidification the reverse of this process); (2) *evaporation*, for the change from the liquid state to vapor (the term boiling is used when the whole mass of the liquid participates in the process; the reverse of the process is called condensation or liquefaction); and (3) *sublimation*, for the direct passage from the solid state to vapor (with the same term used for the reverse process).

SUBLIMATION

When a solid substance fuses due to heating, when it boils and vaporizes, and when these vapors are collected and cooled so that the original solid is reconstituted, then the process of distillation has taken place. In every respect this distillation is analogous to the distillation of a liquid. On the other hand, a substance that is solid under normal conditions sublimes when it volatilizes at a certain temperature (which is defined as a function of the pressure). In this case the vapor will recondense directly to the solid state; there will be no intermediate formation of a liquid.

To prevent a solid from passing through the liquid state prior to vaporization, the pressure exercised on the phases must not exceed the value of the vapor pressure at the triple point. This can be achieved by reducing the pressure of the system with a vacuum pump.

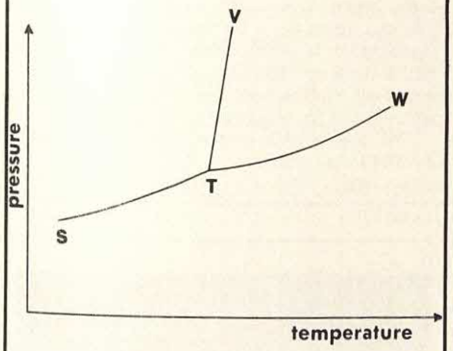
Generally this process is called sublimation under vacuum.

Even though sublimation theoretically defines both the direct passage from solid to vapor and from vapor to solid, it is the latter change that is exploited in practice. Actually, the substance subjected to sublimation often is so impure that its fusion point is considerably lowered; in the initial stage of the process it will, therefore, first fuse and then evaporate, yet the vapors formed will recondense directly to the solid state without passing through a liquid phase.

FUSION

The fusion point of a crystalline solid is the temperature at which the solid transforms itself into a liquid at a pressure of one atmosphere. If the substances are pure, this change of state is sharp and well defined (although for experimental reasons it is estimated as taking place in an interval of at least 0.5–1.0° C); the fusion temperature is, therefore, an important figure for characterizing a sub-

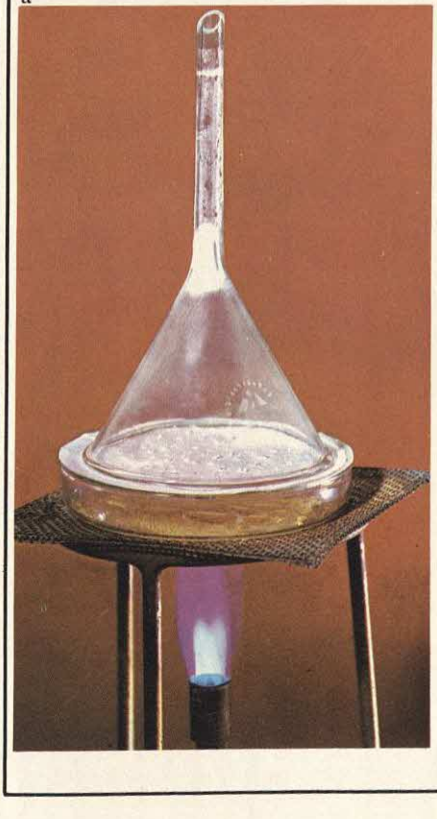
1



SUBLIMATION CONDITIONS — This graph shows the equilibrium between solid, liquid, and vapor phases. **T** is the triple point and defines the temperature and pressure at which the three phases coexist; equilibrium between any two phases is obtained along the curves **ST** (solid-vapor), **TV** (solid-liquid), and **TW** (liquid-vapor). The graph clearly shows that at a pressure below the triple point, a vapor can pass directly to the solid state when the temperature is sufficiently lowered and vice versa. This kind of graph can be drawn for each substance that can be characterized by two particular values of the temperature and pressure that correspond to the triple point.

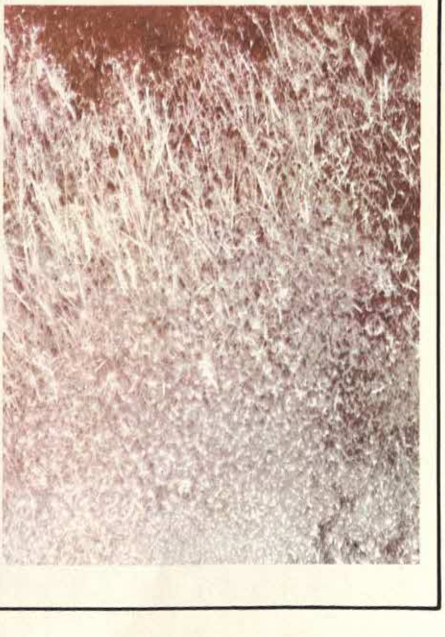
2

a

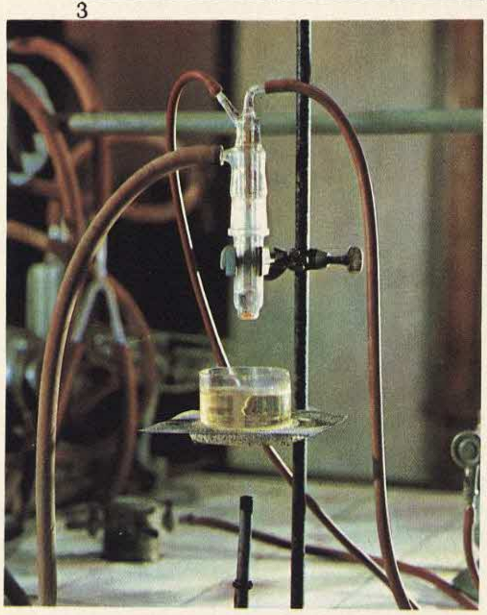


SUBLIMATION — A sublimation occurs when the substance to be sublimated (sulfur, in this case), evaporates, crosses through a piece of filter paper, and condenses on the cold walls of a funnel (Illustration 2a). Illustration 2b shows a sublimate of benzoic acid.

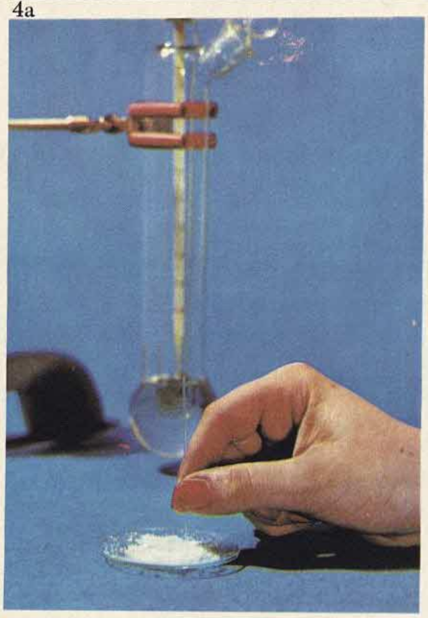
b



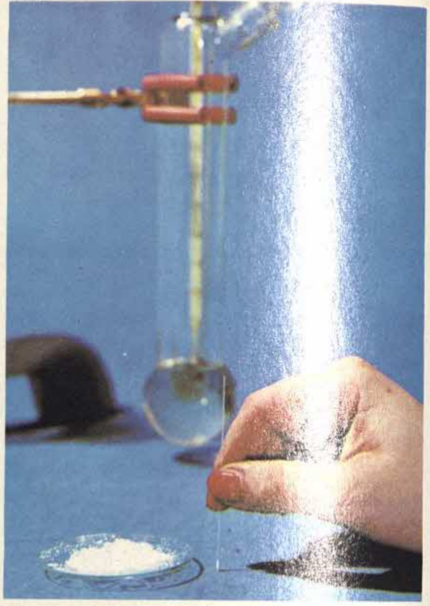
3



4a

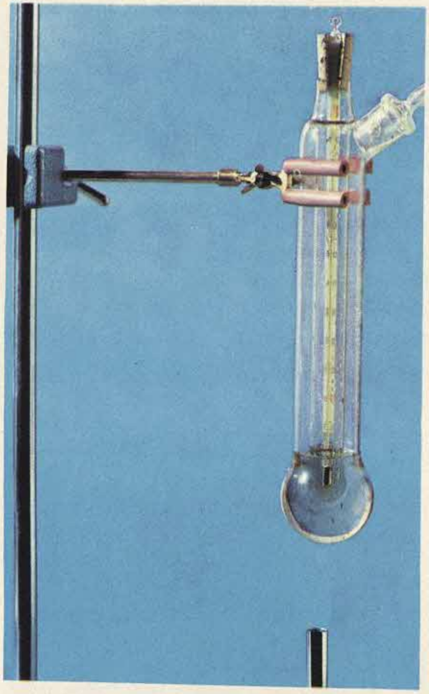


4b



SUBLIMATION UNDER VACUUM—The basic apparatus used for this experiment consists of two components held together by a friction joint. The lower component is a glass cylinder containing the substance to be sublimated. The upper component, an outer glass sleeve that fits over the cylinder, has an inner glass tube that passes into the cylinder. Cold water is circulated in this tube, the "cold finger." The outer sleeve also has a lateral opening that is connected to a water pump used for creating a vacuum in the lower cylinder or, more precisely, for reducing the pressure from its normal atmospheric value (about 760 mm of mercury) to a much lower figure (20 mm of mercury, for example). The apparatus is then immersed in a bath, arranged in such a way that the level of the external liquid reaches as far as the cold finger. Next, the bath is slowly heated. When a high enough temperature has been reached, the solid vaporizes, and the vapor recondenses when it comes in contact with the cold walls of the finger, where it will deposit in the form of minute crystals. On completion of the experiment, the upper part can be lifted out of the bath and the deposited solid scraped off. This is an excellent way to purify substances, especially when the substances cannot be obtained by ordinary crystallization. All the impurities will be at the bottom of the lower cylinder.

4c



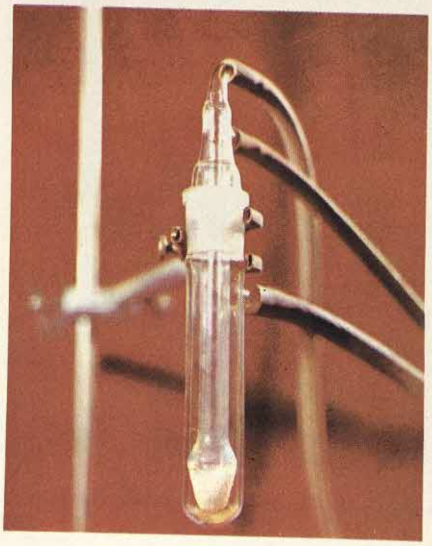
DETERMINATION OF THE FUSION POINT—For this experiment, a small capillary tube, closed at one end, is used. It has a diameter of about 1 to 2 mm (about 0.04 to 0.08 in.) and a length of about 7 to 8 cm (about 2.3 to 3 in.). The substance is placed on a glass dish or clean porcelain tile, where it is finely pulverized with a spatula and arranged in a small heap. The open end of the capillary tube is immersed in the heap, and the tube is then lightly tapped to make the substance enter into it (Illustration 4a); the tube is now turned upside down and again tapped very lightly until all of the substance has settled compactly at the bottom (Illustration 4b). The filled tube is attached to a thermometer in such a way that its closed end is about level with the middle of the mercury bulb; the thermometer is wetted with the liquid in which it will later be immersed so that the capillary tube will adhere to it. The liquid bath (Illustration 4c) consists of two concentric and noncommunicating glass tubes; the two receptacles are filled with the same liquid, care being taken to make sure that the liquid level is the same in both; the thermometer is then placed into the inner container. This arrangement, by ensuring gradual and even heating, reduces to a minimum possible errors in reading the thermometer.

The double bath and a small flame ensure an accurate reading.

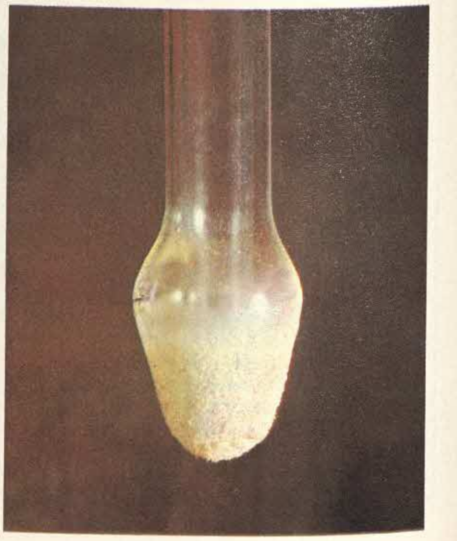
5

THE SUBLIMATION AND THE SUBLIMATE OF 1-4 NAPHTHOQUINONE—This type of apparatus also can be used to carry out a sublimation under vacuum. The substance (1-4 naphthoquinone) is placed in the outer sleeve, which is connected to a vacuum pump by the lower rubber tube. The outer sleeve is evacuated (Illustration 5a). The two upper rubber tubes are used to circulate water in the inner receptacle, called the cold finger. The vaporized substance recondenses on the outer walls of the cold finger in the form of pure crystals (Illustration 5b). The maximum temperature that can be attained with this type of apparatus is 250° C (482° F); it is not advisable to exceed this figure.

a



b



6

THE KÖFLER PLATE — For substances that fuse at higher than 250° C, it is best to use electrical equipment, such as this Köfler plate. A very small quantity of the substance is placed on an electrically heated plate and is observed through a microscope. A thermometer is connected to the plate so that the temperature can be read. The plate itself is protected by a glass disk that isolates it from variations in the environmental temperature.

stance. The very pure substances (at any one given pressure) fuse at a fixed and very precise temperature, so much so that many of them are used for calibrating thermometers. This is particularly true in the case of metals with an extremely high degree of purity. The inaccuracy of 0.5–1.0° C, which can occur in determining the fusion points of even very pure substances, can be traced in most cases to experimental error resulting from the methods and equipment used.

The constancy of the freezing point of a pure substance is so characteristic that change of the freezing point is a convenient test of the presence of foreign material.

Impurities will considerably enlarge the range in which the fusion of a solid takes place; thus, liquefaction will begin at a temperature lower than the one at which the substance would fuse if it were pure, and complete fusion will occur over a range of temperature that may cover several degrees. The passage from the solid to the liquid state (and vice versa) is the only process that is barely influenced by the pressure; in fact, even large variations of pressure produce only modest variations of the fusion state.

The experimental method for determining the fusion point of a substance consists of heating, in a capillary tube, a small quantity of the substance. The tube is attached to a thermometer and immersed in a liquid bath whose temperature is raised very gradually. The liquid with which the bath is filled can be concentrated sulfuric acid, oil of petrolatum, or silicone oil: the important thing is to use a liquid with a very high boiling point.

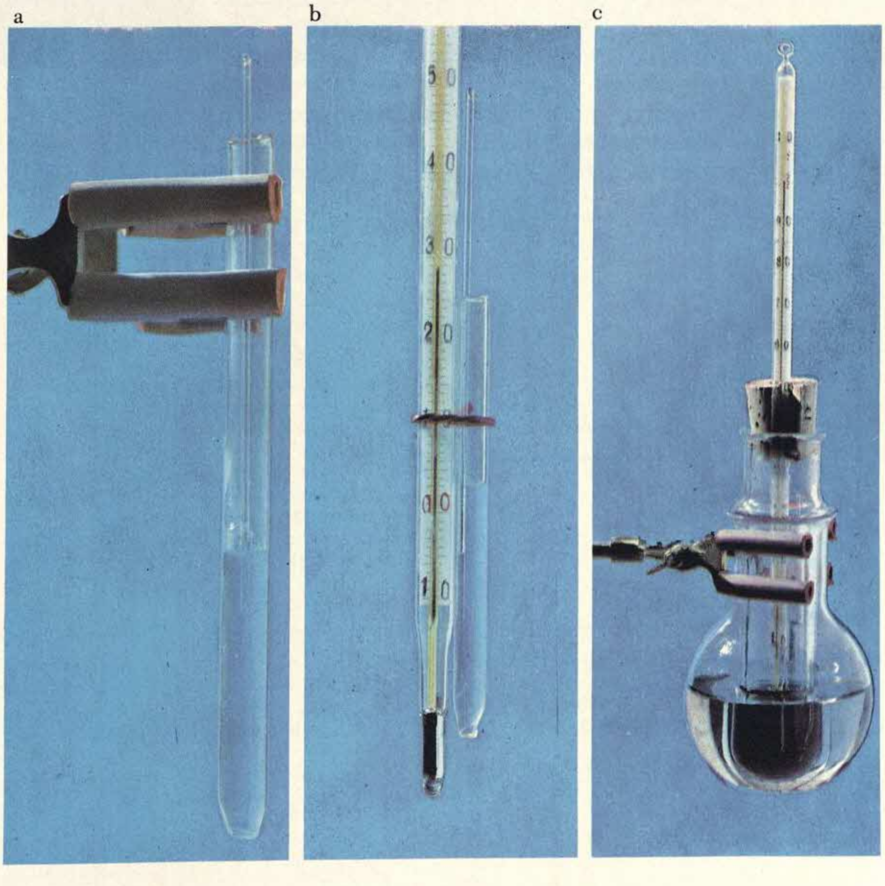
BOILING

The boiling point of a substance is the temperature at which the vapor pressure equals the pressure exerted on the system. How is this temperature determined?

If enough of the substance is available, a proper distillation can be achieved. The liquid is heated until brought to a boil; the vapors liberated from the mass of the liquid will rise to the thermometer, whose temperature will eventually become stabilized at a value that can be assumed to be the boiling point of the substance. If only a small quantity of the substance is on hand, some micromethod must be used.

7

SIWOLOBOFF'S MICROMETHOD—Two glass tubes, closed at one end, are used. The first is a capillary tube 90 mm (about 3.5 in.) long, with a diameter of 1 mm (about 0.04 in.). The second tube is 80 mm (about 3 in.) long and has a diameter of 5 mm (about 0.2 in.). A small quantity of the liquid is placed in the larger tube, and the open end of the capillary tube is immersed in this liquid in a way that will leave some air trapped above the liquid (Illustration 7a). The two tubes are then attached to a thermometer with an elastic band (Illustration 7b), and the thermometer is placed in a double-flask arrangement similar to the one used in determining the fusion point (Illustration 7c). The air in the capillary tube dilates as the bath is heated; furthermore, it escapes from the bottom of the capillary tube in the form of bubbles, and is replaced by the liquid's vapors. The discharge of bubbles becomes rapid and continuous as the boiling point of the liquid is reached. The flame is then removed. As the temperature falls, the number of bubbles diminishes, and at a certain point only one bubble is left, remaining poised at the bottom of the capillary tube almost as if it were uncertain whether to escape or allow itself to be sucked back into the tube. This means the external (atmospheric) pressure acting on the bubble is exactly equal to the pressure of the vapor in the capillary tube. The equality of these two pressures reveals that the liquid is exactly at the boiling point, and the temperature can be noted by reading the thermometer at this moment.



THE MELTING POINT | from solid to liquid

When a solid crystalline substance is heated to a certain temperature, it begins to liquefy or melt; the temperature at which this occurs is the melting (or fusion) point for that substance (at a given pressure). Inasmuch as noncrystalline substances such as glass do not change directly from the solid to the liquid phase, they have no melting point.

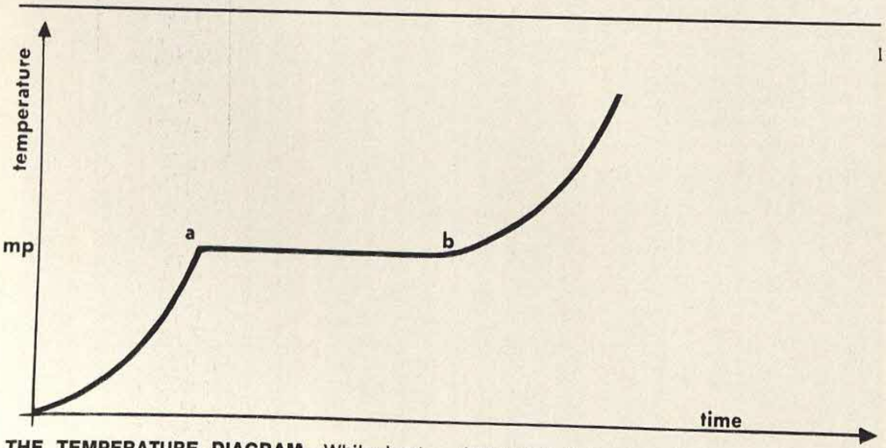
The forces that bind the molecules together—the intermolecular forces—are the factors that determine whether a substance is a solid or liquid (or gas). If the bond is strong enough to maintain the molecules in a fixed, rigid position in relation to each other, the substance is a solid; however, if the molecules can move with some freedom, without altogether escaping from one another, the substance is a liquid. Any energy that enables the molecules of a solid to weaken their intermolecular force to the extent that they attain relative freedom of movement will, in effect, cause the solid to melt. The energy capable of melting a crystalline solid is provided by heat.

Different substances have different melting points, depending on their molecular structures. It is possible, therefore, to identify the molecular structure of a substance, and the substance itself, by measuring the amount of heat—the temperature—required to bring about melting. Chemists take advantage of this measurement for analysis, especially when trying to identify certain organic substances that are otherwise difficult to distinguish from one another. Among the hydrocarbons, for example, individual members of the paraffin series have almost identical chemical properties, but each melts at a specific temperature; this characteristic makes it easy for a chemist to identify a particular paraffin in the series.

The melting point of a substance also depends to some extent on the degree of its purity. If its crystalline lattice contains atoms of another substance, the lattice will tend to break down in the vicinity of these extraneous atoms; the entire substance will tend to melt at a slightly lower temperature if it contains impurities (although in some cases this happens at a slightly higher temperature, because of the nature of the impurity). Thus, the determination of the melting point of a specimen of a substance, whose melting point in its pure state is known, provides a test for its purity, and this tool is also used by chemical analysts.

Some substances cannot be tested or identified by measuring their melting points because they decompose at a lower temperature than would theoretically be required to melt them. Wood, for example, because of its cellulose and lignin components, eliminates volatile substances (gases) when heated and carbonizes instead of melting. Many organic substances and a few inorganic substances behave similarly; it is useless to attempt to melt them.

Certain characteristics concerning the melting process can best be discovered by experiments. A useful preliminary to experimentation is the preparation of a graph showing the temperatures at successive moments while the substance is being heated at a constant rate.



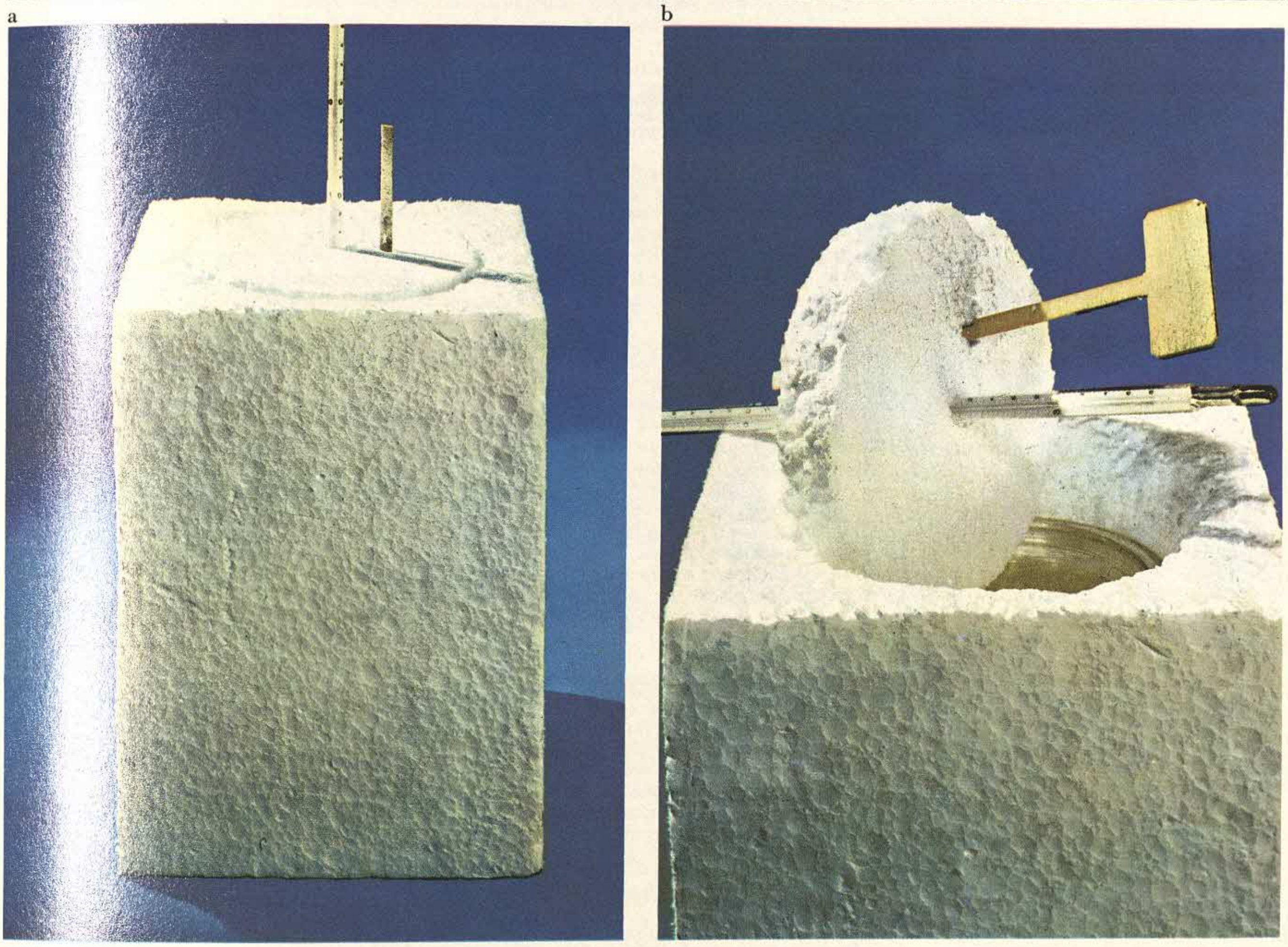
THE TEMPERATURE DIAGRAM—While heating a substance at a constant rate, the temperatures reached should be recorded at fixed time intervals. At first the temperature will rise; when it has reached the melting point **a**, it will level off even though heat continues to be applied. When the entire substance is melted **b**, the temperature will again rise.

TEMPERATURE DIAGRAM

A substance should be subjected to the heating process while well below its suspected melting point. As the heating continues, the temperature of the substance will continue to rise for a certain length of time, and this can be recorded on the graph. After a certain time the temperature will no longer rise, even though the heating is continued, and the graph will show a level line instead of a rising line for that period. This phenomenon is caused by a change within the substance. As long as the temperature rose, the molecules were being increasingly agitated by the added heat energy, until the stage was reached when the stable positions that characterize the molecules of a solid could not be maintained. In order to detach these molecules and destroy the crystalline structure, energy is required, energy provided by the heat. In other words, heat that had up to now increased temperature was diverted into the task of liberating the molecules from their rigid bonds—the critical changeover from the solid to the liquid state.

This moment, when an increase in heat is not reflected in a rise in temperature, is the most delicate part of the experiment because it proves that the substance has reached its melting point. The substance is now partly in a solid phase and partly in a liquid phase. Heating must continue in order to act further on the molecules that are still solid; but this heating will also act on the liquid molecules, which will be in direct contact with the walls of the container. As a matter of fact, the liquid molecules will have a temperature slightly greater than the solid molecules; if it is desired that the substance melt rapidly, considerable heat must be applied, and the temperature of the liquid will actually be above the effective melting point of the substance. This information will be supplied by the thermometer immersed in the liquid, which will indicate the real melting point and the greater temperature of the liquid.

2

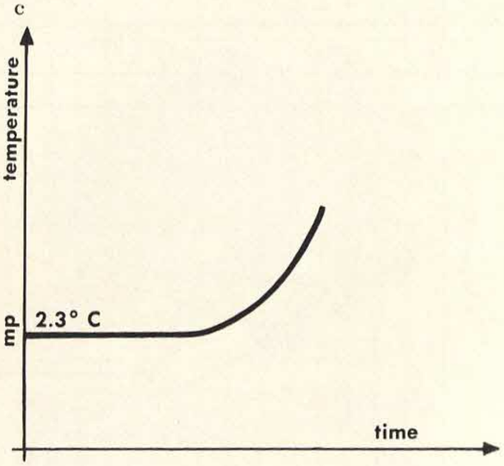


THE MELTING POINT OF ICE—It is commonly accepted that ice melts at 0° C (32° F), but it is not easy to find a piece of ice that will melt at this temperature, because even a small quantity of the salts present in water (even drinking water) or of dissolved gases (oxygen, nitrogen, carbon dioxide) will change the melting point. The only ice that will melt at this temperature must be made from water that is perfectly distilled and then boiled to ensure removal of all dissolved gases.

This photograph shows the best way to prepare the ice that will be measured for its melting point. It should be placed in a glass container, such as a 1-liter or 1-quart beaker, along with an equal amount of water; the container and its contents must be thoroughly insulated in polystyrene foam, a commonly used plastic material, which must extend above and below the container (Illustration 2a). Even the removable cover, in which the thermometer and a paddle stick are inserted, must be made of this insulating material (Illustration 2b).

The thermometer must be sensitive enough to measure tenths of a degree. The paddle stick is to be used for stirring when necessary.

The container with the ice and water must be left within the insulation long enough to ensure that the temperatures of the solid and liquid are equal, as shown by the thermometer. Enough heat will filter through the insulation and the container walls to bring this about and to melt the ice, and this will happen so slowly that there will be no difference in temperature between the two phases of water (solid and liquid). The contents can be stirred gently, and the thermometer must be read constantly during the melting process to verify a nearly constant temperature. When the temperature begins to rise, the melting has come to an end. The value of the melting point can then be calculated by averaging all the readings before the rise. In one such experiment (Illustration 2c), the value turned out to be 2.3° C (36.14° F).



3

a

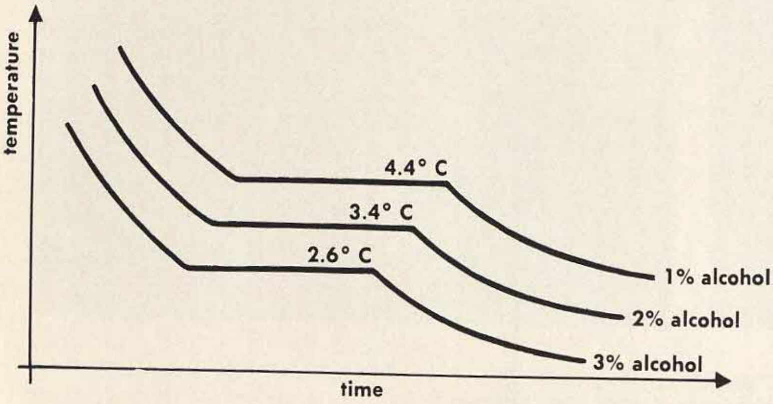
THE EFFECT OF IMPURITIES—In the previous experiment, the solid phase of a liquid (ice or solid water) was used; in this experiment another liquid, benzol, is frozen to its solid form in order to demonstrate some of the phenomena that occur when it melts—particularly when it contains specific quantities of an impurity.

The melting point of benzol is known to be 5.5° C (41.9° F); this is, therefore, also its freezing point. Liquid benzol can be solidified in an ordinary refrigerator, or by applying to it either ice, some other freezing mixture, or dry ice. In order to melt the solid benzol, a little heat from the environment can be allowed to filter gradually into the container, which can be similar to that used in the previous experiment (although it need be only about one quarter the size), and which should be similarly insulated. Illustration 3a shows another setup, consisting of two glass containers, the inner one containing the benzol and the outer one containing the freezing mixture. For the purpose of this experiment, suitable admixtures of an impurity—methyl alcohol, which readily mixes with benzol—will be added to the benzol as indicated. Both containers will be insulated and the removable cover will, as before, accommodate a thermometer and a paddle stick.

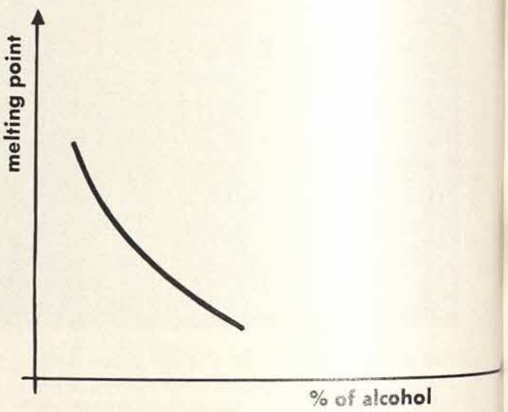
Great care must be taken during the freezing process, during which the benzol mixture will be in contact with the walls of the container holding the freezing mixture; during this time, its temperature will be slightly below the melting point. On the other hand, when the temperature is measured during the melting process, it will be found to be much higher than the melting point; in fact the liquid receives heat from the container walls and transmits it to the substance being melted, and is, therefore, much warmer than that substance. For this reason the heat must penetrate the container very slowly, ensuring a very gradual rise in temperature.

By making a graph of the changes in temperature near the melting point, two complementary values will be obtained. The value obtained during freezing will usually be nearer to the melting point. In Illustration 3b all three graphs were obtained by recording the rising and falling temperatures on each side of the freezing point, using benzol containing three different concentrations of alcohol. The graph in Illustration 3c shows how the melting point is lowered as the percentage of methyl alcohol increases.

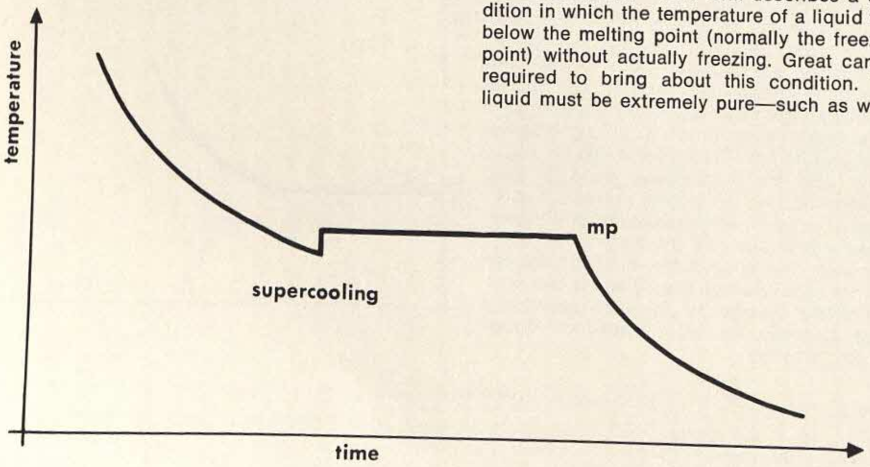
b



c



4



SUPERCOOLING—This term describes a condition in which the temperature of a liquid falls below the melting point (normally the freezing point) without actually freezing. Great care is required to bring about this condition. The liquid must be extremely pure—such as water twice distilled—and placed in a very clean glass container with a very smooth internal surface. The liquid must be left completely still, neither shaken nor stirred. If these precautions are taken, the liquid will cool to a temperature below the freezing point without freezing. At a certain temperature, however, part of the liquid will freeze and the temperature will rise to the normal freezing (or melting) point while freezing occurs. The rapid freezing, in fact, liberates the latent heat of solidification (the inverse of the latent heat of melting—that period in which the molecules are rearranging themselves); this raises the temperature of the supercooled liquid. The graph shows the falling temperature, which passes the freezing point; a very rapid rise to the freezing (melting) point; a period during which the entire liquid freezes; and a further fall indicating that the freezing point has been passed for the entire mass of the liquid.

THE BONDS IN SOLIDS

electrons—the binding forces in atoms and molecules

Imagine, for a moment, what might happen if all the atoms in a mountain were to be lumped together, with all of the space between them eliminated. The result would be an extremely dense, small mass perhaps the size of a tennis ball.

While giving all appearances of being a solid mass of rock, a mountain and everything else taken for granted as being solid is for the most part "empty" space. The atoms in all solids are, in reality, relatively distant from one another. The spaces between them contain the binding forces that hold atoms and molecules close enough to each other to form apparently solid matter.

The science of crystallography is the means by which the positions of atoms within substances can be determined. Based on such study, for instance, the arrangement of the atoms in a molecule of barium titanate ($BaTiO_3$) can be represented as shown in Illustration 1. A crystal of this material can be thought of as a number of polyhedrons formed by the atoms (shown in the illustration as spheres) in a face-to-face arrangement. The lines between the spheres depict the binding forces holding the atoms together, but do not suggest anything concerning the nature of the forces.

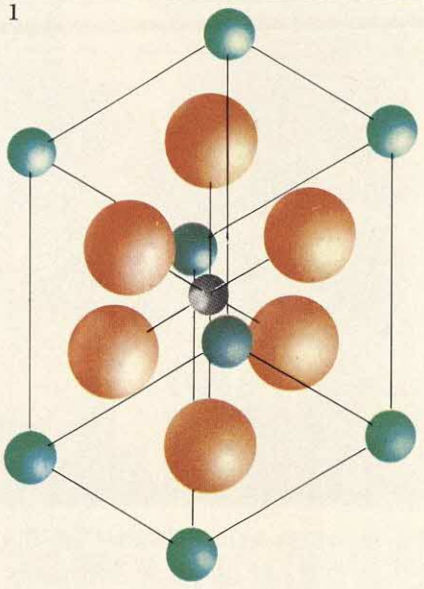
In order to understand the binding forces in solids, all solids may be classified according to the types of bonds linking their atoms and molecules.

IONIC BONDS

Ionic solids are substances in which the atoms are held together by electrostatic forces. Such forces operate between electrical charges of opposite polarity.

Sodium chloride—common table salt—is a good example of an ionic solid. The compound can be made by starting with neutral sodium and chlorine atoms. A sodium atom will give up a negatively charged electron to a chlorine atom, but in so doing becomes a positively charged ion. In the same process, by gaining a negative electron the chlorine atom becomes a negatively charged ion. Because of the resultant opposite charges of the two ions, a strong mutual attraction exists (Illustration 2a). This explains the electrostatic nature of a single sodium chloride molecule.

1



ATOMIC ARRANGEMENT IN A BARIUM TITANATE CRYSTAL—The science of crystallography is the study of the atoms in crystal structures. An understanding of the physical properties of crystalline solids is based on a knowledge of the nature and intensity of the forces holding them together.

A salt crystal (Illustrations 2b and 2c) contains large numbers of sodium ions and chloride ions. If the crystal is to hold together, the arrangement of the ions must be such that the attraction of oppositely charged ions is greater than the repulsion between those of the same charge. When arranged alternately in a cubic lattice, each ion is surrounded only by members of the opposite charge, as shown in Illustration 2b.

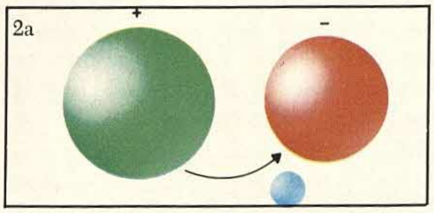
Ions of similar charge are separated by a distance equal to the diagonals of the cubic lattices. This is a greater distance than that between oppositely charged ions. Therefore, the repulsion force is less than the attraction force within the lattice, and the solidity of the crystal is maintained.

Knowing how the atoms of an ionic solid are linked allows the prediction of some of the physical properties exhibited by this type of compound. First, a very strong attraction exists between ions of opposite charge. Therefore, considerable energy is required to destroy an ionic compound by the separation of its composite atoms.

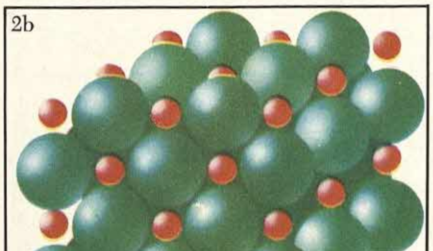
At low temperatures (room temperature, for example), the ions in an ionic crystal are firmly "anchored" to their positions within the lattice, and the electrons associated with each ion are unable to break away. Specifically, this means that the crystal, or compound, will not conduct electricity. There are no freely moving electrical charges within it to conduct a current. At high temperatures, on the other hand, the ions move about and change position when in-

THE IONIC BOND—This type of bond is formed between two atoms when one loses an electron to become a positive ion and the other gains an electron to become a negative ion (Illustration 2a). Illustration 2b shows the arrangement of sodium ions (small spheres) and chloride ions (large spheres) in a crystal of sodium chloride. Illustration 2c is a photograph of sodium chloride, or common table salt.

2a



2b



2c

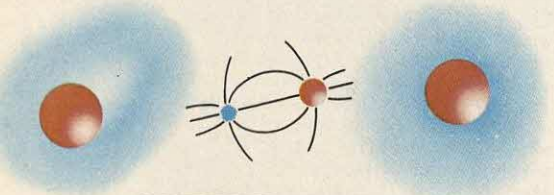
fluenced by an electrical field, giving the compound the property of excellent electrical conductivity.

A further property of ionic compounds is their inability to absorb light passed through them. This, again, is due to the fixed nature of their electrical charges. Because of this property, ionic crystals are transparent. However, short wave ultraviolet radiation can be absorbed by the splitting of electrons from pairs of oppositely charged ions. Long wave infrared radiation is also absorbed, but in the form of heat because it causes the ion pairs to oscillate.

3b

THE MOLECULAR BOND—This type of bond may exist between neutral atoms (atoms having an equal number of positive and negative charges), as shown in Illustration 3a. The molecular bond is also present within molecules, and, further, holds molecules to one another. These bonds hold together the atoms in the solids formed after the cooling of certain gases, of which methane is an example. The erupting gas well in Illustration 3b illustrates burning methane.

3a



COVALENT BONDS

Suppose that an electron is "lost" from the outer shells of each of two atoms, and that these electrons take up new positions between the atoms, as shown in Illustration 5a. The result is a compound having a covalent bond. In fact, atoms may share more than one electron to form covalent bonds. Carbon atoms are connected by such covalent linkages especially characteristic in organic molecules.

A typical covalent crystal is diamond, whose structure is a lattice of tetrahedrons with a carbon atom at each point. The edges of the tetrahedrons are identical to the forces binding the atoms together. It is precisely this structure that gives diamond its characteristic strength and hardness. As much energy is required to destroy the crystal by removing the atoms from the lattice one-by-one as would be needed to disintegrate the ion lattice as a whole.

Because the atoms and electrons are locked in their positions within the lattice (moving electrons are enclosed in the spaces between neighboring pairs of atoms), covalent crystals have almost no electrical conductivity, and are transparent if pure.

METALLIC BONDS

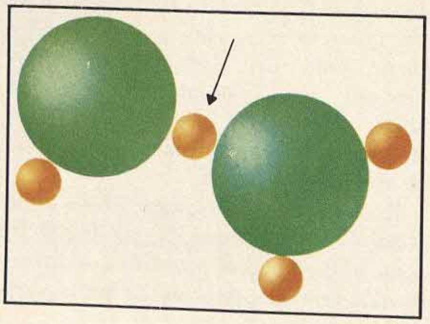
Solids with metallic bonds are composed of a lattice of positive ions with electrons moving between them. Neutral iron atoms, in forming an iron crystal, come into close proximity to one another to form the structure shown in Illustration 6a. Each atom loses one or more electrons, and these can move with relative freedom within the lattice. A metal's crystal lattice can be thought of as a "sponge of positive ions" impregnated with free electrons.

But, how are the iron atoms bound together? Although the positive ions in the lattice have a tendency to repel one another, the cloud of free electrons acts to hold them together. However, because the distances between the ions and electrons in a metal crystal are relatively large, such bonding is weaker than in either an ionic or covalent bond.

The large number of free electrons in metallic solids is precisely the reason for their high degree of electrical conductivity. Moreover, these same electrons

TWO WATER MOLECULES LINKED BY A HYDROGEN BOND—Illustration 4a details the positioning of one water molecule's hydrogen atoms between the two molecules in the structure of water. The hydrogen is "lost" alternately to one and then the other molecule, creating a bond. Ice, illustration 4b, is composed of water molecules linked by such hydrogen bonds. The considerably larger oxygen atoms determine the basic structure.

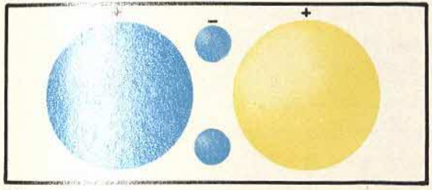
4a



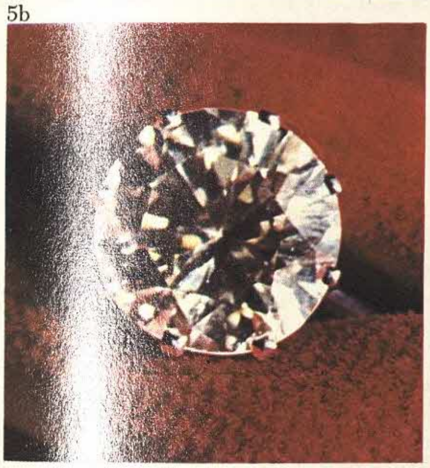
4b

THE COVALENT BOND—A covalent bond is created when two or more atoms share electrons between themselves, as in Illustration 5a. The diamond in Illustration 5b is made up entirely of carbon atoms linked by covalent bonds.

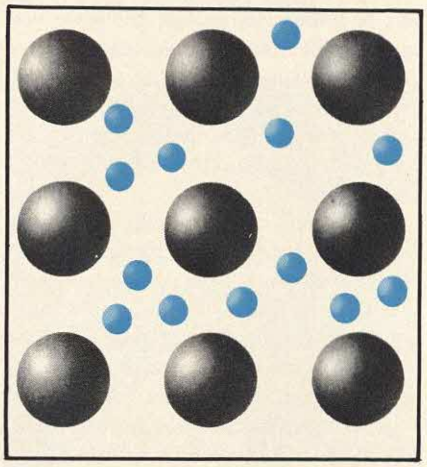
5a



5b



6a



THE METALLIC BOND—In a metal crystal, the atoms each lose an electron. These electrons remain free to move about among the crystal's ions (Illustration 6a). The ions have a positive charge, and the attraction between these ions and the cloud of free electrons creates the metallic bond. The ordinary iron bolt shown in Illustration 6b is made up of atoms linked in this way.

6b

absorb any electromagnetic radiation striking them. This is why metals are opaque, even when they are very thin.

MOLECULAR BONDS

Some atoms and molecules do not lose, gain, or share electrons to form an ionic, covalent, or metallic bond. Such atoms and molecules remain neutral, keeping their entire stock of electrons. Logically, they should not be surrounded by an electrical field—the negative forces of the electrons should be symmetrical and thus balance the positive force of the rest of the atom. However, because of the constant movement of electrons around the nucleus, a part of the atom may be temporarily weak in negative charges if the electrons "bunch up" in one place. In this situation, lasting a fraction of a millionth of a second, the distribution of the negative charges is no longer symmetrical. The massing of negative charges on one "side" uncovers positive charges on the other "side." There are, thus, two poles, creating a dipole, and attractions to nearby dipoles that were formed in the same way.

Thus, even in the absence of other types of bonds, atoms or molecules may be affected by weak forces of attraction pulling them together. These molecular forces are known as Van der Waals forces (named for the Dutch physicist who calculated their effect on the behavior of gases).

Van der Waals forces, being extremely weak, require only a small amount of energy to break the crystals they form. Moreover, such substances are quite pliable and can be deformed using only moderate energy. These same weaknesses in bonding impart low fusion points to molecularly bonded solids. Argon (an inorganic inert gas) and methane (coal, or marsh, gas) are examples of molecular solids when in the crystal state. At ordinary temperatures, they are gaseous. At relatively low temperatures, however, they solidify with ease because molecular motion is not sufficient to rupture the bonds holding their crystals together.

HYDROGEN BONDS

In solids made up of molecules containing hydrogen atoms, a hydrogen atom may lose its single electron alternately to each of a pair of neighboring atoms. The proton is therefore exposed, enabling it to exert a degree of positive attractive force. The strength of this attraction is somewhat greater than in the case of the molecular bond, but considerably less than in ionic and covalent bonds. This type of "link" is called a hydrogen bond or hydrogen bridge. Illustration 4a shows a small hydrogen atom as it forms a "bridge" between two other atoms.

Hydrogen bonding allows various substances such as water (Illustration 4b), hydrochloric acid, and long-chain molecules such as cellulose to crystallize. Of extreme importance is the manner in which protein molecules are arranged in living matter by hydrogen bonds. An example is the protein DNA, the basic constituent of cells.

CRYSTALLIZATION | purity through solubility

The chemist who works in a modern laboratory has a variety of sophisticated equipment available to ease his analytical tasks. Nonetheless, many less automated analytical methods must be applied before sufficient skills are developed to allow effective choice and use of the sophisticated instruments.

One important basic analytical technique—fractional crystallization—takes advantage of the different solubilities of compounds. For almost all substances it is possible to find a liquid in which they will dissolve. Ordinary water is often called the universal solvent because most compounds are soluble in it to one degree or another. Yet there are many substances that will not dissolve appreciably in water, so other inorganic solvents or organic solvents must be used to form solutions.

Every compound has a given solubility per unit volume of solvent. For example, while 100 cc of cold water will dissolve 50 g of sodium thiosulfate, the same volume of water cannot accommodate more than .03 g of iodine. On the other hand, while soluble to only a slight extent in water, iodine will easily dissolve in alcohol, whereas sodium thiosulfate is insoluble in alcohol.

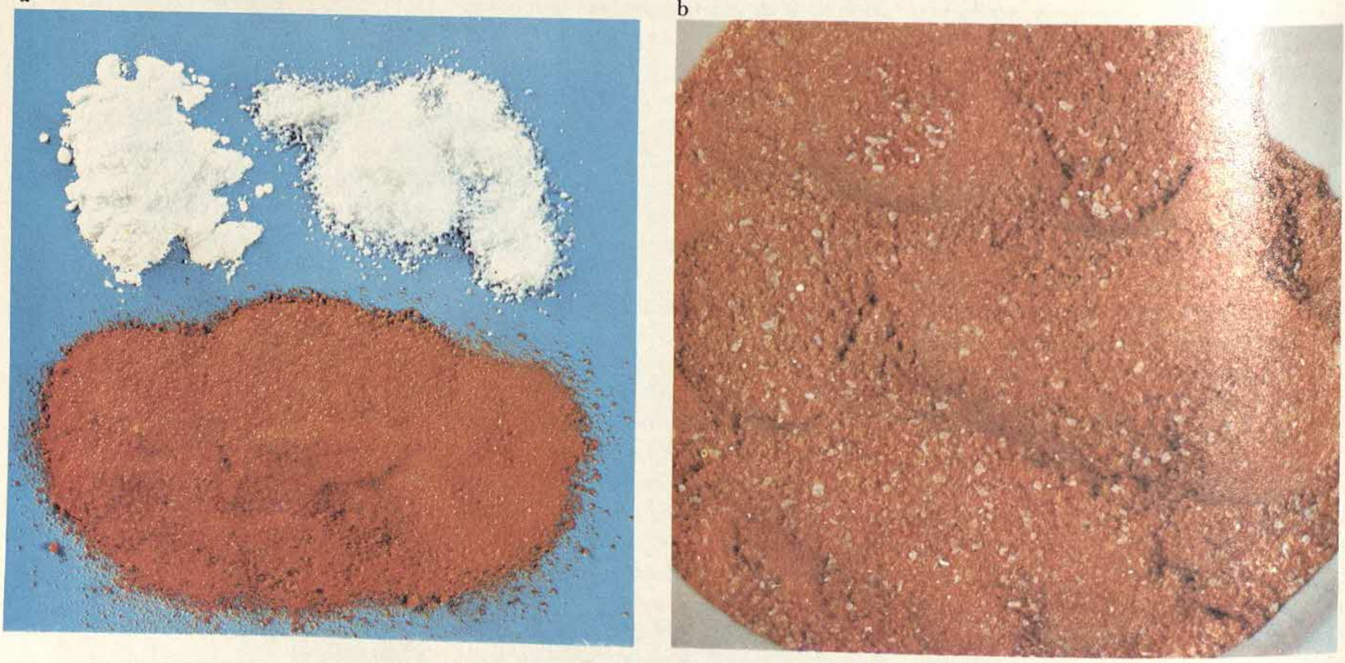
This variation in solubility of a compound in a given solvent makes it possible to separate it from other compounds in a mixture. For example, suppose that a mixture is composed of two materials, one highly soluble in water, the other less so. Dissolving this mixture in water (at a given temperature) results in a solution of the soluble compound but not of the insoluble one. By a process of filtration and evaporation, the soluble compound can be obtained as relatively pure crystals.

This is the simplest example of purification by crystallization. Suppose, however, that the mixture contains two compounds equally soluble in the solvent. Obviously, simple filtration and evaporation will be of little value. (This does not apply when the amount of the "polluting" substance is small compared to the one desired in the pure state.) When the two substances are present in relatively equal amounts, the temperature of the solvent, as well as the solubilities, becomes critical. If the impurity is more soluble than the desired compound, for example, it will remain in solution after cooling the solvent. If the impurity is less soluble than the desired compound, cooling the solution will allow the impurity to separate, or precipitate, leaving the wanted material in solution. Filtration and concentration allow recovery of the material.

Chemists call the recovered compound

1

A MIXTURE OF SOLIDS TO BE PURIFIED— The three solids in Illustration 1a have very different solubilities in water, and are thus separable by crystallization. The ratios of the solids are: 50 g of potassium dichromate, 5 g of sodium chloride, and 2 g of calcium oxide. The mixture of these solids (Illustration 1b) is strictly mechanical, but it is practically impossible to separate the components by hand.



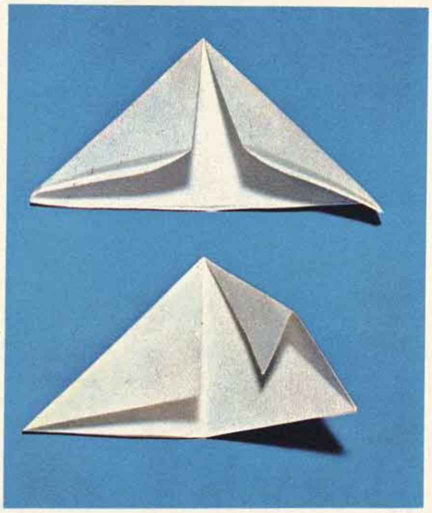
2

PREPARATION OF THE SOLUTION—Both the potassium dichromate and the sodium chloride are very soluble in hot water, while calcium oxide is not. The prepared mixture of these salts is placed in a 600 cc beaker, and about 110 cc of water added. Heating the solution to 90° C (194° F) with constant stirring will dissolve all of the sodium chloride, most of the potassium dichromate, and none of the calcium oxide. (More water may be added to completely dissolve the dichromate.) The water must not be allowed to reach the boiling point. This first step in the purification of the dichromate allows a certain separation of the salts, primarily the insoluble calcium oxide.

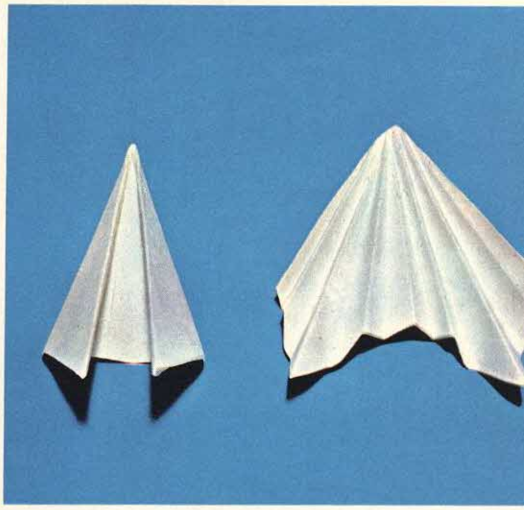
3

PREPARATION OF THE FILTER—Filter paper is a very porous material, and is available in a wide variety of porosity depending on its intended use. Generally, filters are sold by the manufacturer ready for use, but it is a good idea to know how they are prepared for use. In Illustration 3a, a suitably sized square of filter paper has been cut and folded in half twice. The process is continued until the shape shown in Illustration 3b is achieved; final folding results in the shape shown in Illustration 3c. The filter must be cut to fit the funnel; the top of the filter is about one-half inch below the rim of the funnel (Illustration 3d).

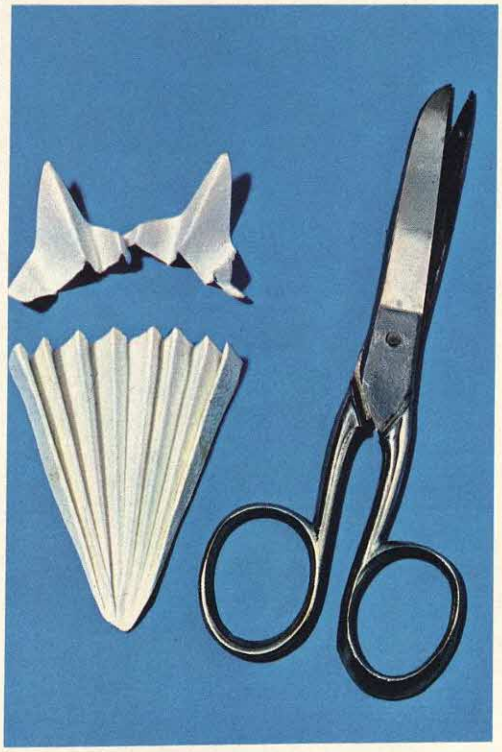
a



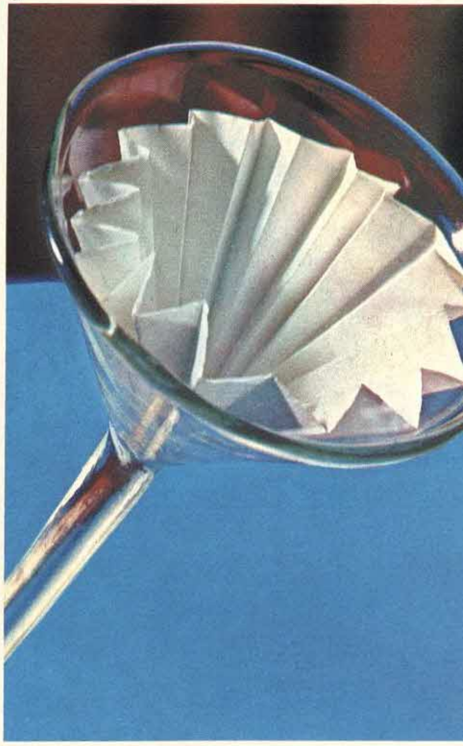
b



c



d



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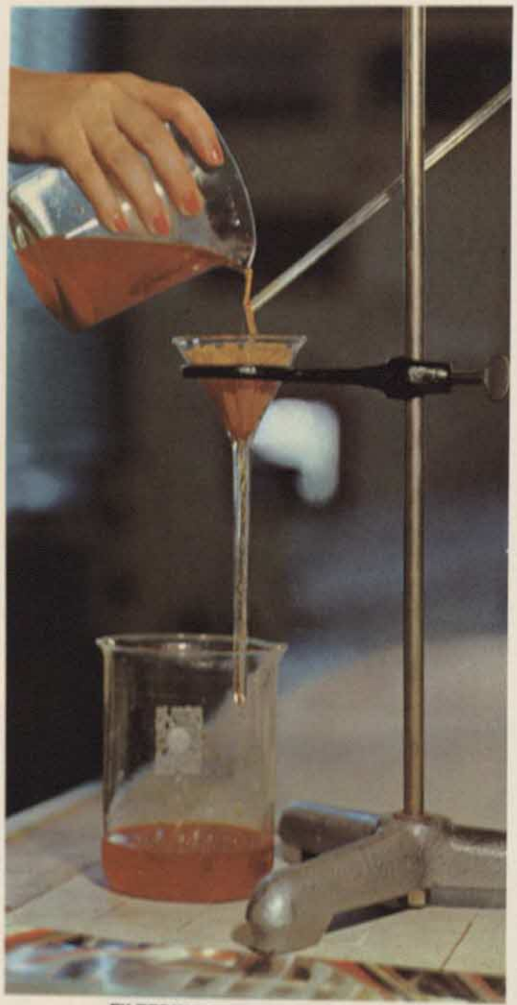
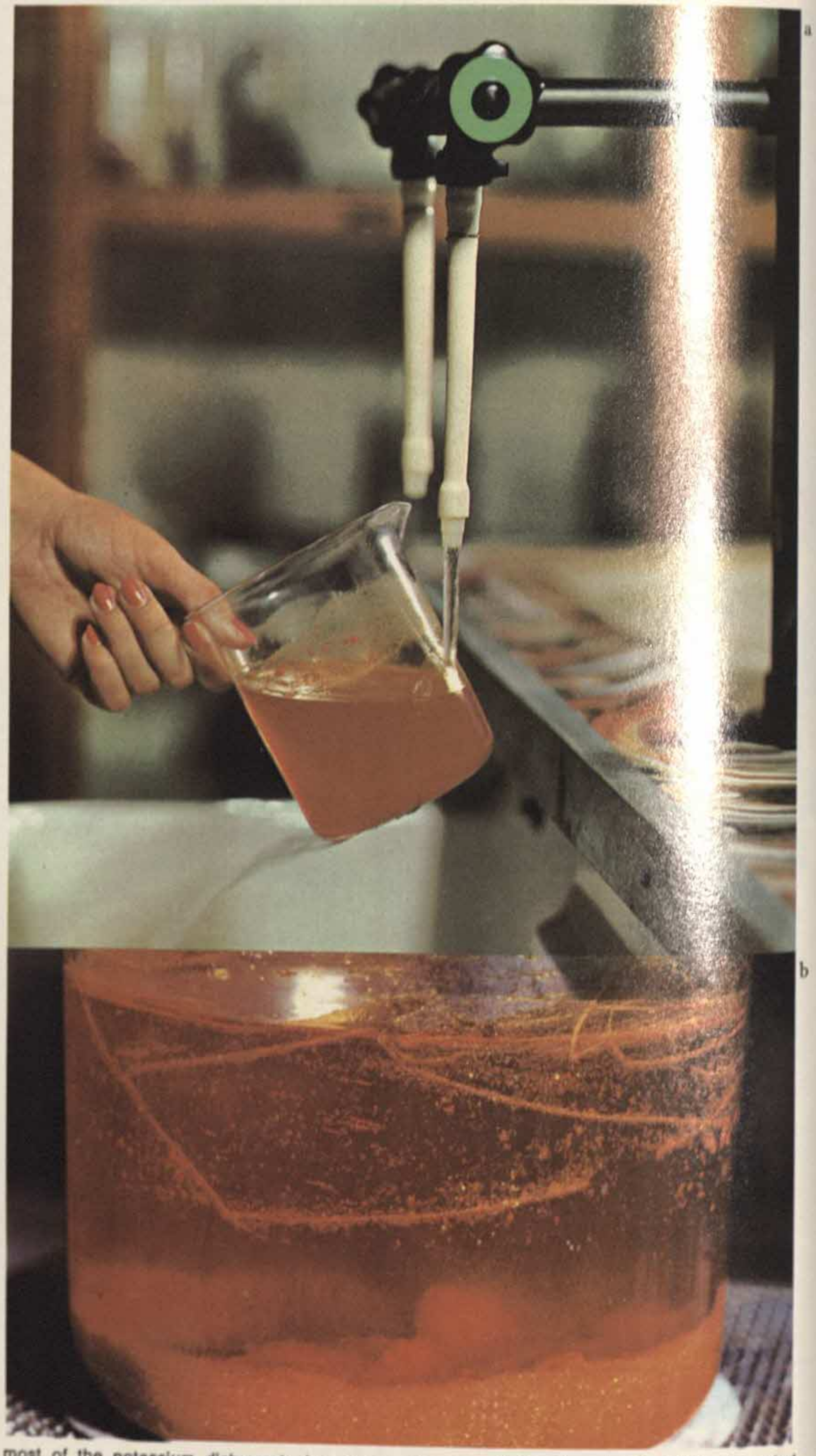


5



FILTERING THE SOLUTION—The purpose of filtration is to remove solid impurities from the dichromate solution, in this case calcium oxide. The temperature of this operation is important to prevent premature crystallization of the dichromate. Therefore, before the filter is placed in the funnel, boiling water is poured through the funnel to heat it. Then, with the filter in place, the dichromate solution is poured quickly into the funnel, using a glass rod to assure a steady flow. Passing rapidly through the filter into another receptacle, the potassium dichromate begins to crystallize.

PURIFICATION OF THE POTASSIUM DICHROMATE—Following the first filtration, the funnel and its filter are carefully removed (so as not to break the filter paper) and the solution allowed to cool. Cooling can be accelerated by running ice water over the container of solution (Illustration 5a). The lowering of the temperature forces the dichromate out of solution, where it immediately crystallizes into large and small grains, as in Illustration 5b. Most of the sodium chloride remains in solution because of its greater solubility in cold water. This solution is allowed to stand until most of the potassium dichromate has crystallized, and then is filtered once more. After the second filtration, the liquid is discarded and the crystals allowed to dry.

the yield: this is very rarely, if at all, the total amount of the material. The purification process involves a loss; thus, yields are given in percentages (30 percent, 60 percent, 99.999 percent, for example).

OBTAINING A HIGH YIELD

The quantity and purity of a yield can be improved over that provided by simple dissolution and filtration. One such improvement can be achieved by maintaining constant temperature of the solution throughout the procedure. In this case, the temperature would be that of maximum solubility of the desired compound. Ideally, none of the compound should be lost. Practically, the yield will not be exactly 100 percent because some of the material will cling to the filter paper.

Assuming that the solvent is water (as is generally the case in inorganic chemistry), another method used to improve the yield utilizes an excess of water. If, for example, 50 g of a mixture of potassium dichromate and sodium chloride is dissolved in water at 90° C (194° F), the solution can be filtered without premature crystallization of the dichromate (the yield, in this case). When the filtered solution is boiled and begins to evaporate, the dichromate begins to crystallize. At this point, the solution can be cooled to near 0° C, allowing the dichromate to reach its maximum point of crystallization. The sodium chloride, being more soluble, remains in solution.

A second crystallization will result in an even purer yield of dichromate, since some of the sodium chloride will still be attached to the dichromate crystals. The procedure is the same as in the first crystallization. In the final analysis, the presence of sodium chloride in the potassium dichromate is very small—on the order of 1:10,000,000. If, as sometimes happens, a solution does not crystallize, the solution may be inoculated with a minute crystal of the same substance or a similar one to achieve the desired result.

6

PURE SALT—After the second filtration, the potassium dichromate looks like this.

7

DRIED POTASSIUM DICHROMATE—The filtered salt is allowed to dry in air. The final yield, in this example, is 40 g of dichromate, or 80 percent. The loss results from part of the material having remained in solution and part lost during filtration. Thus, the final proportion is obtained by the equation 50 g : 40 g = 100 g : x g. (where x = yield).

THE FORMATION OF CRYSTALS

the consequences of lattice defects

"Clothes do not make the man." This is true to a certain extent, for in judging a person, the usual procedure is to assess his personality, his intellectual capacity, his mental and emotional reactions. His outward appearance, although not a primary consideration, does however contribute to the final estimate made of a man; clothes, therefore, have their own peculiar importance. Similarly, in the study of a crystalline structure, ordinarily only the internal portions of the crystal are considered. It so happens that a structural element, such as a base or cell, is always viewed as forming part of a practically unlimited series of other cells or bases in all three dimensions. Therefore, all the phenomena that take place on the surface of the crystal are substantially neglected. Yet these phenomena are of considerable importance in the formation, or growth, of crystals.

Actually, crystallography is not concerned with the phenomenon of crystal formation. Nevertheless, this phenomenon is vitally important from many other points of view. The crystalline structure terminates at the surface of the crystal; here the perfection of the structure is marred because the atoms of the surface stratum are subject to forces of attraction and repulsion exercised from only one side of the plane that defines the surface itself.

It is, therefore, very important to study the discontinuity surfaces of the crystalline structure, which consist of the crystal outline; that is, the faces terminating these crystals.

The same crystal may grow in different forms. It may be cubic or octohedral, for example, to cite but two common variants of the same simple structure. The termination of a crystalline face assumes great importance in the structure because the crystalline structure is forced to improvise at these faces. The structure arranges itself so that the potential energy existing because of the reciprocal attractions exercised by the atoms assumes a minimum value. The way these atoms attract each other at the surfaces of the crystalline germ (that is, the base agglomerate from which the polyatomic aggregate of the fully grown crystal will develop) determines the form that will be assumed by the crystal itself.

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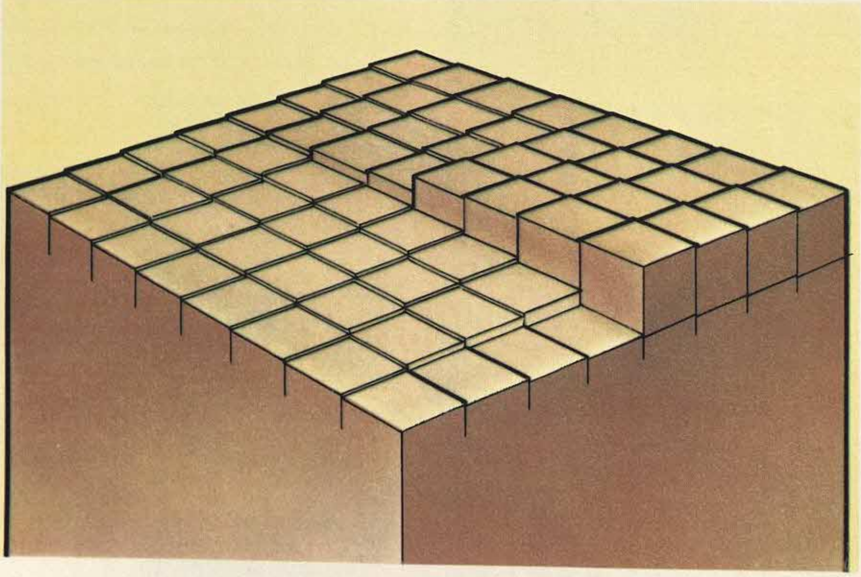

DISLOCATIONS AND CRYSTALLINE SURFACE—What happens when dislocations occurring within the body of the crystal present themselves as a line of dislocation at the surface of the crystal?

The illustration shows a screw-type dislocation on a crystal's surface. Actually, the surface terminates somewhat in the manner of a spiral staircase. Especially to be noted is the way this dislocation produces some particular discontinuities on the crystal surface—discontinuities that take the form of steps. These steps constitute the points where an atom or ion from the medium that supplies the material for the growth of the crystal (supersaturated solution, vapor, supercooled liquid) can easily attach itself. "Easily" here should be understood as meaning more easily than would be the case on a perfectly plane surface; for a surface of this kind, in fact, would constitute a barrier to the growth of the crystal.

CRYSTALLINE IMPERFECTIONS AND GROWTH

Even a solely theoretical understanding of the phenomena that take place on the faces of crystals is extremely important for predicting the behavior of crystalline structures. This is especially so in the case of crystals that consist of microcrystalline bodies in which the atoms affected by surface phenomena form a considerable proportion of the total.

In a large and well formed crystal of transparent quartz, for example, the atoms that form its surfaces are very few when compared to the atoms that form its body. The fact that they are arranged so that their potential energy, atom by atom, is much greater than that of the crystal's other atoms, has only a small influence on the characteristics of the crystal itself. On the other hand, in a polycrystalline aggregate consisting of extremely small crystals, the surface atoms do not by any means form a small proportion of the whole; quite the contrary, they constitute an important segment. Furthermore, the characteristics of their exceptional arrangement will affect the properties of the whole substance. For example, the outlines of the crystalline grains are (1) places where a very rapid diffusion may take place, or (2) areas where corrosion phenomena are likely to occur.

The characteristics of the crystal surfaces also govern the crystal's rate of growth. In fact, it has been calculated that if the crystal structure were to terminate at the faces just as faultlessly as a theoretically perfect crystal, the rate of growth would be about $e^{3,000}$ times less

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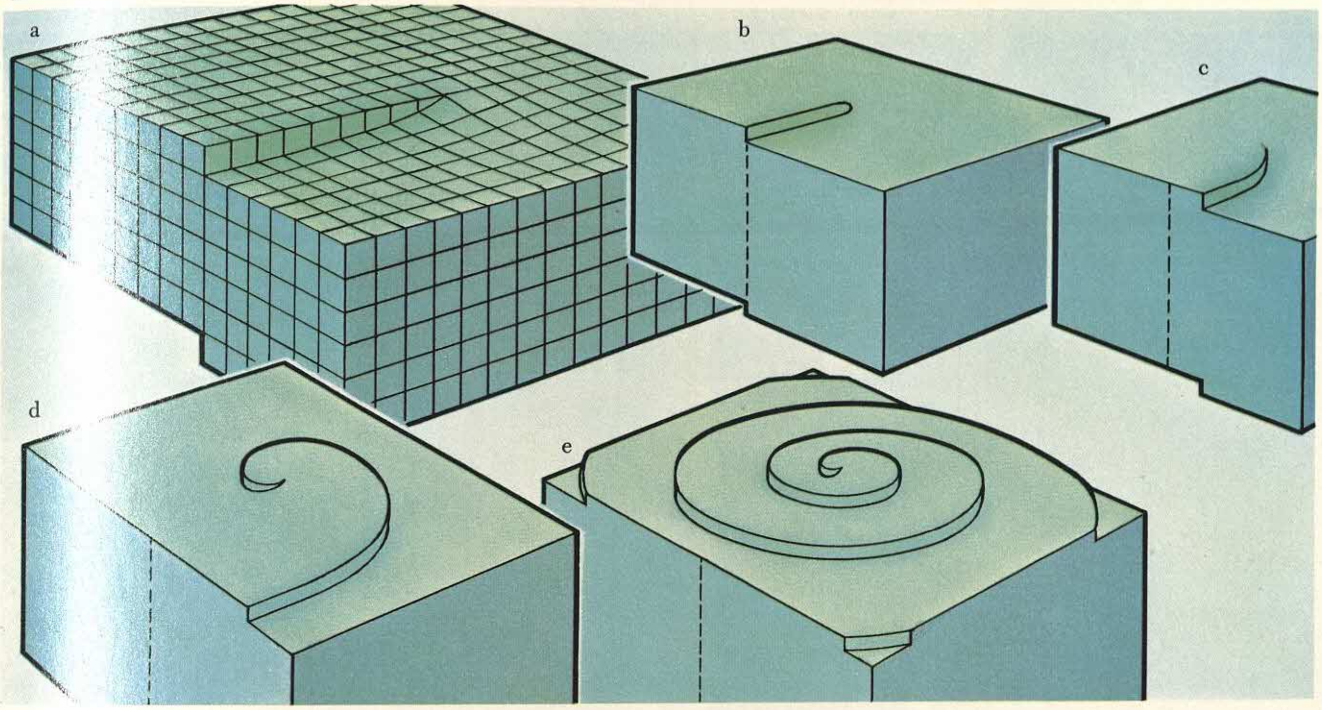

GROWTH ON SCREW-TYPE DISLOCATIONS—This series of illustrations shows how a crystal grows when a screw-type dislocation appears on one of its faces.

The screw-type dislocation seen in Illustration 2a consists of atoms, although these are not shown; the position in which these atoms have to be located is marked by the intersection of the sides of the cells, which can be imagined as simple cubes.

Illustration 2b reproduces the same face and the same defect noted in Illustration 2a. The position of the defect where the growth occurs is shown by a darker color.

The part where the step reaches a height corresponding to a complete atomic layer, that is, a small distance away from the axis of the dislocation, is the place where the growth is most rapid (Illustration 2c). The raised level will, therefore, grow in the direction indicated. This is the first stage of growth.

A later stage in the growth (Illustration 2d) shows how and in what manner the step has been lengthened.

A very advanced stage of growth (Illustration 2e) shows how an entire spiral has formed on the surface of the face that constitutes the growth front. The lower part of the spiral has now reached the sides of the crystal; and it has stopped there, improving and adapting itself to the forms that are dictated by the faces of the lateral surfaces of the crystal.

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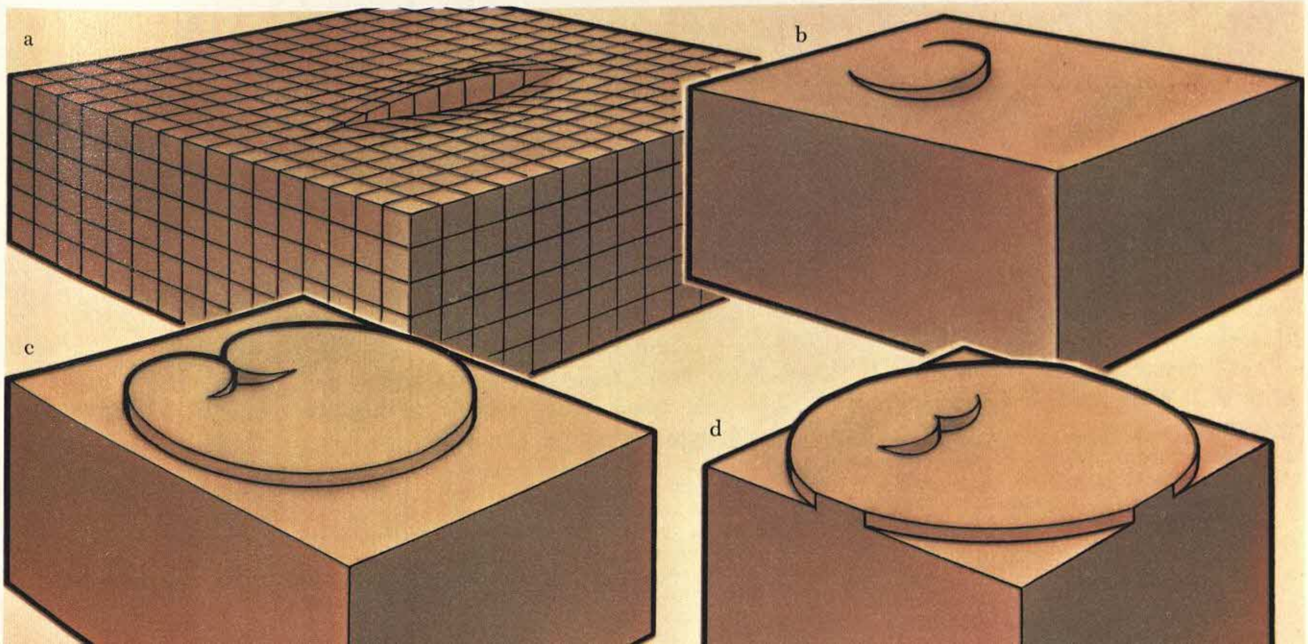
GROWTH ON A PAIR OF DISLOCATIONS—A pair of dislocations, connected as shown in Illustration 3a, does not give rise to a prolonged step, but only to a well-delimited segment in the length within the limits of the face on which the dislocation appears.

Illustration 3b shows the manner in which the atoms have attached themselves to the front of the step, causing the front face of this step to grow at a higher level, with an outline that for conventional purposes only will be considered circular.

At a more advanced stage of growth, a whole platform has been formed, covering the face (Illustration 3c). The platform continues to grow at the back of the dislocation line, which has been re-formed.

In this stage of the growth (Illustration 3d), the added layer has returned to cover the dislocation line and to re-form it in the same position in which it was at the beginning, even though for the moment it appears with a circular outline. It later returns to being rectilinear. The growth will continue this way until the supply of the material needed for forming the crystalline structure has been exhausted.



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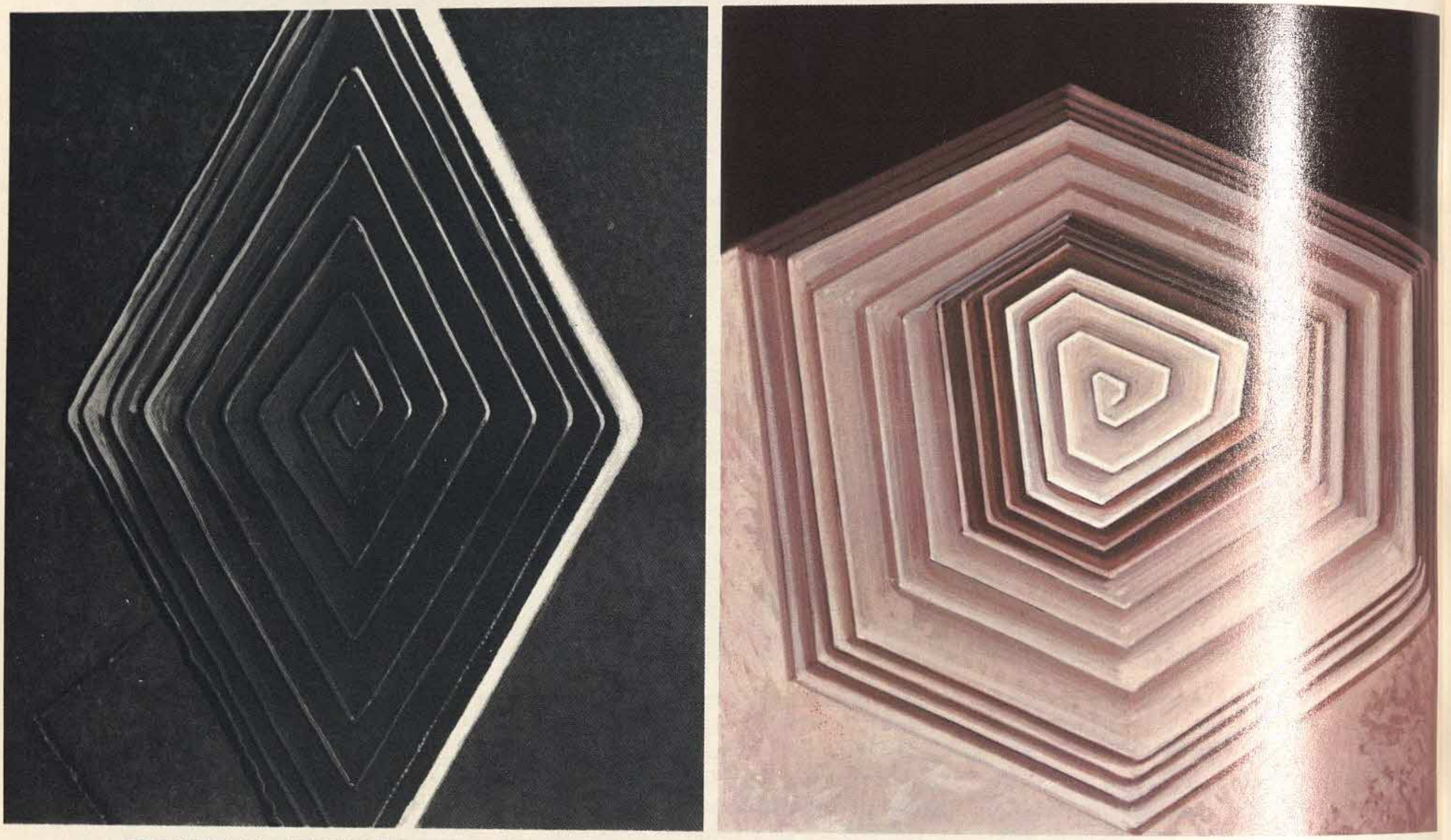

THE FORM OF THE GROWTH STEPS—The form assumed by the growth front need not be circular or spiral; this (in the preceding illustrations) was an approximation. In practice, the front adapts itself to the form of the crystal and its structure. The form can vary a great deal from one crystal to another, but it will generally be polygonal rather than circular in shape.

Illustration 4a is the growth surface of a crystal of paraffin n-$C_{36}H_{74}$. The form of the steps is polygonal or, more precisely, rhomboidal.

Illustration 4b is a polygon on a crystal of cadmium iodide. This time the form is hexagonal.

These illustrations are photographs taken by an optical microscope with a magnification of the order of a few hundred. Analogous figures can be observed on crystals of different types: on polymer crystals, for example. Electron microscopes are also used to take such photographs that show highly magnified details of crystal structure.

than the rate of growth observed in practice. If, for example, a sodium chloride crystal were placed in a 1-percent aqueous solution of sodium chloride, the crystal should grow. If the crystal were perfect, a number of calculations suggest that it should grow at a rate of about $10^{1,000}$ times less than the rate that can actually be observed in practice. This means the crystalline faces really are highly imperfect. The fact that all crystals can grow at appreciable rates indeed proves that no real crystal is ever perfect; and many of the most important properties of a crystal are caused by the few odd places where the crystal structure goes wrong.

The following paragraphs discuss those characteristics of crystalline surfaces that will permit the crystal to grow whenever it finds itself in a favorable environment.

THE SCIENCE OF NEW MATERIALS

The examination of the imperfections of the crystalline surface has progressed beyond its essentially physical and speculative aspects to the point where it has become a study for the production of new materials. In fact, it is now possible to produce crystals of particular form, very long, free from certain types of crystalline defects, and possessing great tensile strength. These are new substances only in the sense that scientists have succeeded in producing them in new crystalline forms that are free of the defects that lead to weakness; their chemical composition is the same as that of the ordinary materials.

For example, it has been found possible to produce crystals of tin with a tensile strength as much as a hundred times greater than that of the ordinary metal, which is known for its plasticity and lack of strength. No practical application has yet been found for this new tin; yet such applications have been found for ruby fiber, which can today be grown with a tensile strength double that of the strongest steel used in making steel cable. Tensile strengths as high as 1,400 kg/mm^2 (about 2,000,000 psi) have been attained in laboratory specimens; these crystals are almost five times as strong as the strongest steel used in cable. Today these fibers are used to produce plastic laminates with fiber reinforcement. The strength of these laminates exceeds that of any metal, yet their weight is considerably less.

The study of crystal growth thus has paved the way to a new science that examines and produces materials of truly exceptional strength.

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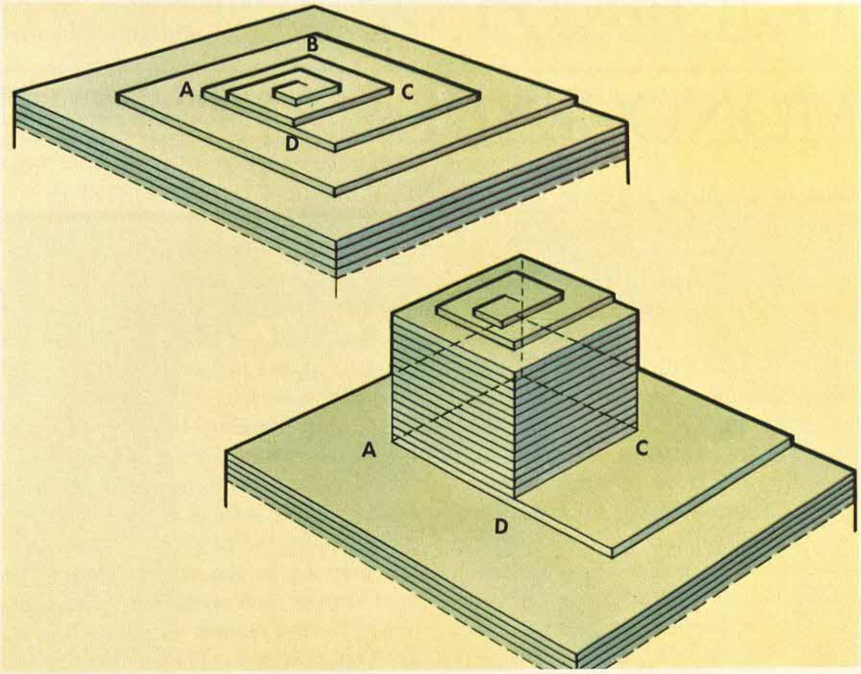
DENDRITIC GROWTH (WHISKER)—In certain cases the spiral growth can be brought to a halt or limited by the presence of impurities. The impurities will stop the growth at certain points, and the growth can then proceed only in a particular direction. Note the rectangle **ABCD** on the surface, where a spiral growth is taking place. A poisoning phenomenon has occurred along the line **AD** of the step; this means some impurities have been trapped here and these have prevented the face of the step from extending in a horizontal direction. The poisoning has been sufficient to ensure that the growth will continue only on the more restricted face **ABCD.** A very thin crystal will now develop on this face, but it can grow to an extremely great length. A crystal formed in this manner is generally called a dendrite or whisker. The characteristic feature of this type of crystal is that it is almost devoid of the particular defects of crystalline structure responsible for plasticity. It therefore possesses the mechanical properties that theory predicts for perfect crystalline substances. These properties are not always desirable; however, in some instances they can be very useful, especially when they produce exceptional strength.



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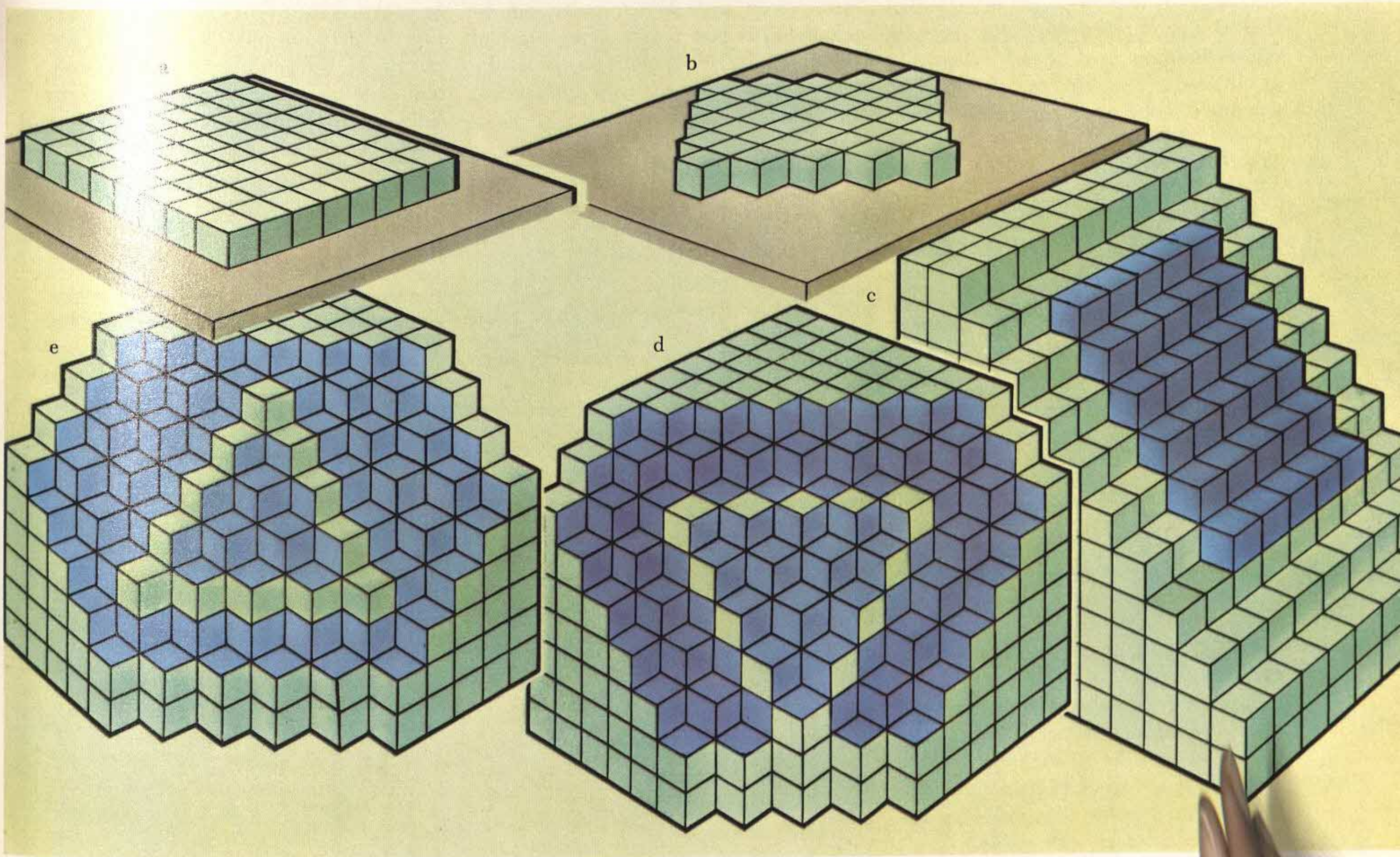

GROWTH BY NUCLEATION—Dislocations are not the only type of crystalline defect that permits the growth of the crystalline faces. The phenomenon of growth also can be promoted by the formation on the faces of the crystal of particular structures called nuclei. The nuclei draw their origin from a defect that causes atoms to cluster around it in the manner illustrated. Step faces are formed on the surface, permitting the crystal germ to extend in a horizontal direction. For the growth of the crystal to proceed even further, it is necessary for another germ to form on one of these layers. These illustrations show how various nuclei are formed ent faces of a cubic crystal: on f (Illustrations 6a and 6b); on faces 0 tration 6c); on faces 111 (Illustration 6e). In all cases the growth will occ faces of the step that are shade darker color.

THE BIRTH OF A MONOCRYSTAL

perfection from chaos

Some of the finest free-form art in the world can be observed through a microscope. Nature has a way of fashioning aesthetically appealing combinations of matter that can be observed by the person who knows where and how to look for them. Crystals are a case in point, and their formation in itself is an absorbing subject of study.

Most solid substances consist of a mosaic of crystals. These crystals are apparent in igneous rocks, for example, where the granular structure can be clearly seen. However, other substances, metals for instance, do not display their crystalline structure as clearly as igneous rocks even though they, too, are made up of crystals. For example, the type of brass used for door handles is made up of different crystals, yet the naked eye can detect nothing that suggests that its structure resembles that of granite. The crystalline form of metals becomes evident only when they are treated in a suitable manner and then examined under a microscope.

POLYCRYSTALS AND MONOCRYSTALS

The crystals of a piece of granite are made up of various substances. The three most common types are quartz, feldspar, and mica. They can be distinguished quite easily when a piece of granite is examined. If a block of paraffin is broken, the surface of the fracture discloses many crystals; however, all these crystals are made up of the same substance: they are not three chemically different substances. Because granite and paraffin are composed of many individual crystals, they are said to be polycrystalline substances.

If the crystals found along the fracture surface of the paraffin are examined, it will be found that each of these crystals can be defined as a true monocrystal. The term *monocrystal* means that the lattice planes throughout the volume of the crystal are all parallel to each other. However, the entire block of paraffin is not a monocrystal because it is made up of a large number of crystals. Unless special precautions are taken, a polycrystalline aggregate will always be obtained when a substance is solidified from the liquid state; seldom will a single crystal form from the whole mass of the solidifying liquid.

THE ISOLATED MONOCRYSTAL

A monocrystal taken from a mass of paraffin was formed by the solidification of a certain quantity of liquid. The cooling of the liquid first led to the formation of a tiny crystal; the molecules of this crystal gradually were joined by others, and the crystal thus continued to grow as long as it was surrounded by liquid paraffin.

At a certain point, however, a further increase in the volume of the crystal was prevented by the presence of other crystals growing in the same manner. The final form of each crystal was thus determined by the manner in which it managed to grow in the limited space left to it by its neighbors. The crystal would have displayed quite a different form if it had been allowed to grow freely. This form would have been regular, not irregular as it was found in the mass of paraffin; also, it would have been the typical form associated with this particular substance.

CRYSTALLIZATION

Nature offers examples of crystallization in the form of both monocrystals and polycrystals. Igneous rocks show polycrystalline crystallization; on the other hand, a large quartz crystal with its characteristic form is an example of a monocrystal.

The formation of a monocrystal from a solution or melted material, either by evaporation of the solvent or by cooling, leads to an interesting discovery: the resulting substance is purer than the one that formed the liquid. In fact, while the crystal is growing from the liquid surrounding it, the atoms or molecules separate from the liquid in order to join those that are already properly arranged in the crystalline lattice of the solid. Only the atoms or molecules of the substance that forms the solid are attracted by the cohesive forces of the crystal. The formation process of the crystal may, therefore, be said to constitute a kind of purification process of the liquid. Obviously the impurities in the liquid will become more and more concentrated as the liquid solidifies. If the crystal is removed from the liquid before the solidification process is completed, the result is a crystal in the pure state.

For this reason, whenever it is necessary to obtain substances with a high de-

A POLYCRYSTALLINE AGGREGATE OF SODA ALUM, $NaAl(SO_4)_2 \cdot 12H_2O$ — These crystals were obtained by normal crystallization using a saturated solution at a temperature of about 70° C (158° F).

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gree of purity, they are made to crystallize in the form of a monocrystal. One such substance is germanium, a material used in the manufacture of transistors.

In other cases it is necessary to obtain polycrystals. Many scientific and technical activities require the crystallization of certain substances in the form of polycrystalline aggregates. For example, a polycrystalline end product is obtained when sugar is extracted from sugar beets; the result is refined sugar. In such cases it is important to make certain that the crystallization takes place so that a large number of crystals are formed, each of which has only limited possibilities of growth.

THE PREPARATION OF MONOCRYSTALS

Since good monocrystals can be obtained rather easily from a solution of soda alum, this substance will be used in the following experiment. Soda alum, whose chemical formula is $NaAl(SO_4)_2 \cdot 12H_2O$, is obtainable from drugstores and other outlets selling chemical products.

First a saturated solution of this salt must be obtained. Soda alum is a highly soluble salt; when it crystallizes from solutions (in the form in which it is normally used commercially), its molecules form crystals that also contain water molecules in their lattices. It is therefore said that crystalline soda alum contains water of crystallization. This water is so abundant that soda alum will melt when it is heated to no more than 61° C (about 142° F). Strictly speaking, the soda alum does not melt; it is more correct to say that the sodium and aluminum sulfates dissolve in the water of crystallization.

Soda alum is highly soluble in water, of course; in fact, water can dissolve a quantity of soda alum in excess of its own weight.

Therefore, the alum (200 g, for example) in a half glass of water must be dissolved at a temperature not exceeding 40° C (104° F). The alum has to be added to the water very slowly, until it is obvious that it no longer dissolves and a saturated solution is obtained. Great care is necessary: the liquid must be saturated while it is hot; the solubility of salts will usually increase as the temperature increases.

Next, all the crystals that did not dissolve must be extracted from the solution, which is then left to cool slowly to room temperature. As the temperature of the solution drops, crystallized alum will become visible on the walls of the receptacle. Careful observation will disclose that here and there on the walls and bottom of the receptacle (a heat-resistant beaker) a large number of crystals have formed. As the temperature continues to fall, these crystals will increase in size and number (Illustration 1).

The lowering of the temperature has

MONOCRYSTALS OF SODA ALUM—The regularity of the octahedrons, shown below and in Illustrations 5 and 6, depends on the precautions taken during the crystallization. The form of the monocrystal depends on that of the germ. The crystal in Illustration 6 is disproportionate because some faces have grown more than others.

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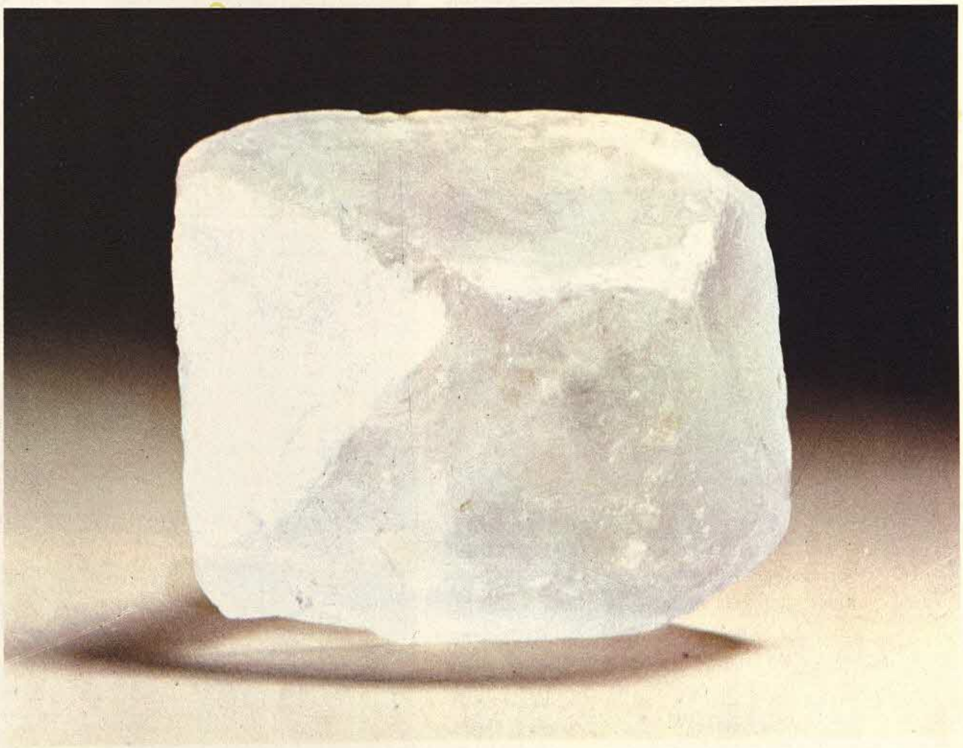

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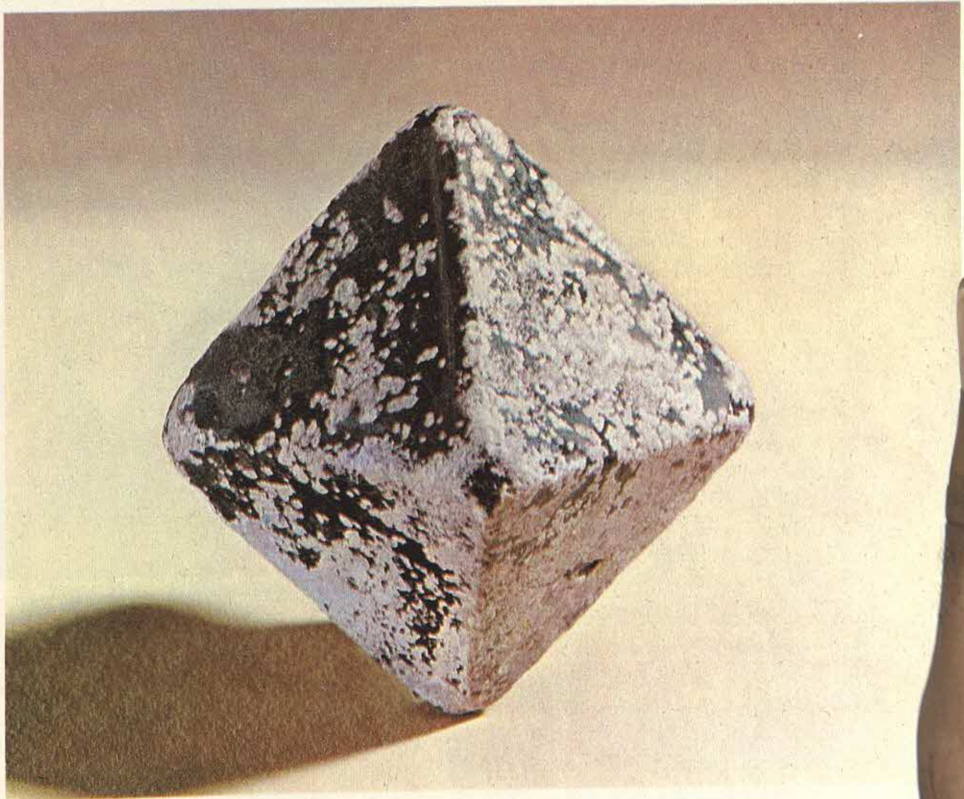

A PERFECT OCTAHEDRON OF CHROME ALUM, $K_2SO_4 \cdot Cr_2(SO_4)_3 \cdot 24H_2O$—There is no doubt that this crystal belongs to the cubic system. The light spots on the surface are due to the chrome combining with the oxygen in the air to which the crystal has been exposed.

caused the saturated solution to become supersaturated with salt, and the salt, therefore, begins to deposit in places congenial to crystallization.

What this means is that the crystallization begins where the salt molecules can attach themselves to some impurity in the water or to some practically invisible unevenness in the walls of the receptacle. The rapid decrease of the temperature forces the molecules to find a large number of points where they can attach themselves and begin the process of crystallization.

THE GERM STARTS THE CRYSTALLIZATION—If a small alum crystal obtained from a previous crystallization is placed at the bottom of a beaker containing an alum solution (Illustration 4), a monocrystal will form, providing the solution is allowed to cool slowly and gradually.

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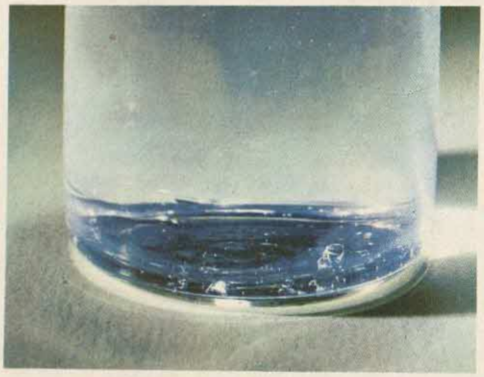

OBTAINING A MONOCRYSTAL

The purpose of the experiment, however, is to obtain a single monocrystal. To avoid conditions that lead to the formation of a large number of crystals, a certain procedure must be followed.

In the first place, a pure solution is essential. If the salt is dirty, the solution will have to be filtered to remove the impurities. This can be done with a funnel and a piece of cotton wool. The beaker should have very smooth and completely clean walls. Also, the temperature must be maintained at a constant level to allow the liquid to evaporate. Lastly, a crystalline "germ" (Illustration 4) must be introduced. If the first crystal is permitted to form spontaneously from the solution, many crystals may form and some of them will appear on the walls of the beaker in undesired positions. It is better to use a crystal previously removed from the solution on the bottom of the beaker. For best results the crystal should be suspended from a thin metal wire, for then the molecules will find it easier to attach themselves to this crystal than to form some other germ of growth somewhere else in the liquid.

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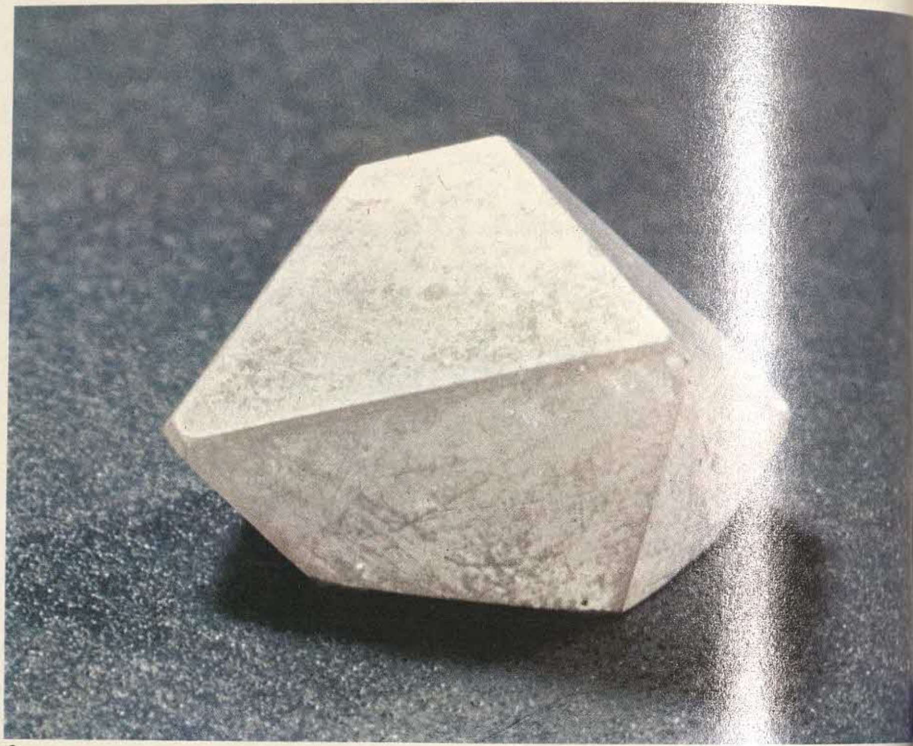

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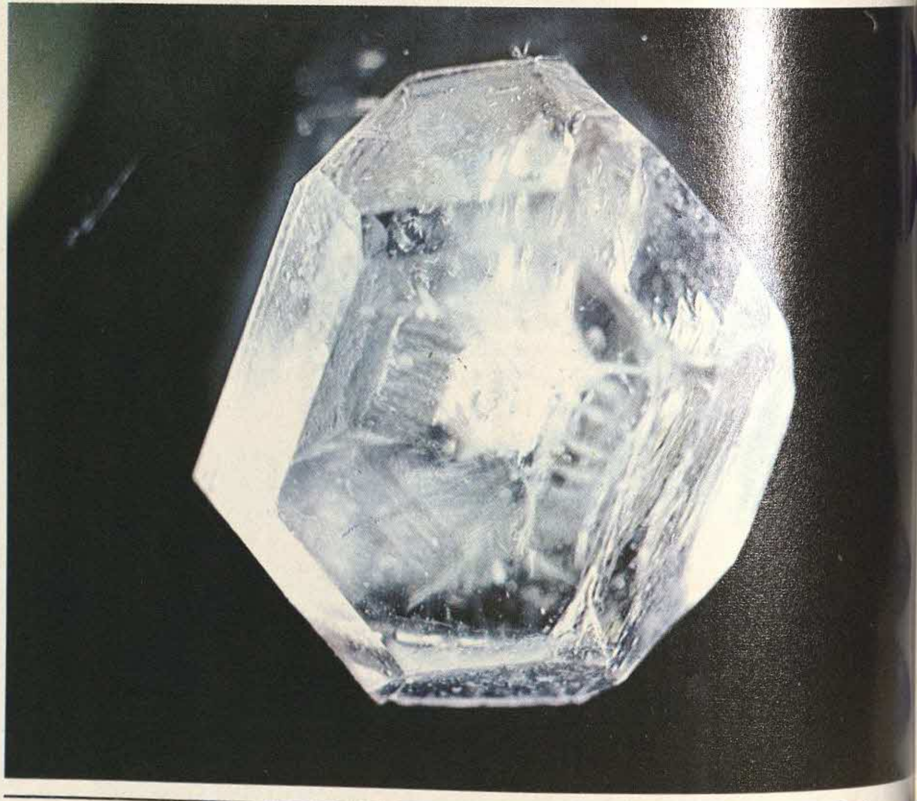

Alum crystallizes in octahedrons. Pure and transparent alum octahedrons (Illustrations 5, 6, and 2) can be obtained provided (1) the solution has been sufficiently purified and (2) the temperature can be kept constant and the evaporation continuous.

During the crystallization process, other growth centers may form, leading to the formation of other crystals. However, this is not a serious mishap, for if they grow very much they can be carefully removed.

The form of the "germ" introduced will determine whether or not the crystals obtained are similar to ordinary octahedrons.

CRYSTAL STRUCTURES | the arrangement of bases in the lattices

In order to understand and describe the many forms that crystal structures take, it is necessary to proceed from the atomic level, discovering the simplest ways in which crystal lattices can take shape. This line of investigation leads to the definition of the fundamental Bravais lattices, of which only 14 exist. The difficulties mount when the researcher advances from the simplicity of the Bravais lattices to the forms of the more common crystals. The following discussion, therefore, deals mainly with the lines of analysis required for the interpretation of the complex crystal forms. The first consideration is that the Bravais lattices are nothing other than crystal lattices or spatial designs that, in real crystals, regulate the arrangement of the molecules of which these crystals are composed. Therefore, it is necessary initially to review the concept of base and structure. A base is the molecule forming a particular substance by virtue of the arrangement of the atoms of which it is made up, while the lattice represents the position in which the bases fix themselves, one at each point of the lattice structure.

While the Bravais lattices are limited in number to 14, innumerable bases exist, even if the research is confined to considering only the elements, excluding all chemical compounds. In fact, not all the elements have the tendency to associate their atoms in the solid state with the same simplicity that characterizes such metals as gold, copper, or platinum. Such metals as uranium, for example, have molecules comprised of large numbers of atoms, and each of these strange molecules constitutes a base of an exceedingly complicated structure.

The complexity of crystal structure quite obviously increases if research is expanded to include the bases of inorganic substances; that is, of the more common minerals. At times these bases can be constituted by molecules with very few atoms, such as sodium chloride. However, the molecules can also be made up of a very large number of atoms, as is the case with certain complex minerals, such as the vanadates and many others comprised of elements with very high valences.

Great complexity is also commonly found in compounds with molecules bound together in chains. The silicates, for example, are made up of molecules of rather modest dimensions, generally containing only a few atoms. However, these molecules have a tendency to be linked in chains. Thus, in studying these crystals it is important to take into account the chain bond when considering the overall structure. The greatest complexity is

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THE STRUCTURE OF MAXIMUM DENSITY— This structure is typical of the crystalline state of those elementary substances held together by forces of the metallic, or the Van der Waals, types.

These forces, especially the ones of the metallic type, act in all radial directions around the atom. Consequently, there are no problems involving the arrangement of the atoms in preferential directions. The structure formed in all these cases will be the densest possible; that is, the structure in which the atomic spheres arrange themselves so that residual space will be at a minimum.

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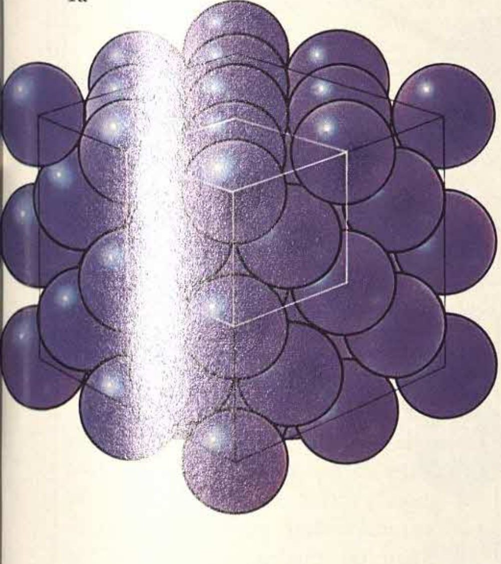

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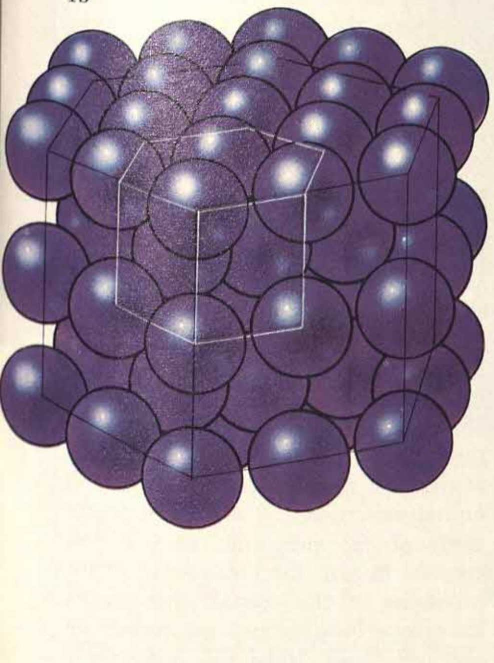
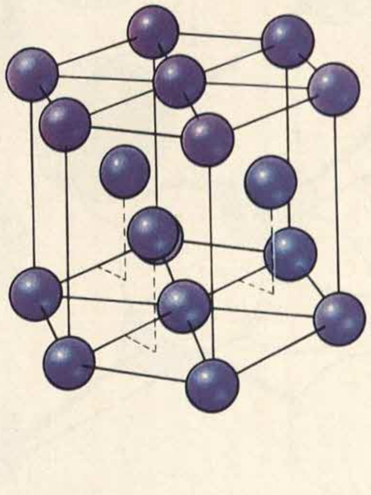


Two possible arrangements achieve the minimum space when the spheres are identical in size. The first of these is the face-centered cube. The base in this particular case consists of a single atom, and the lattice will, therefore, present itself in the simple form shown in Illustration 1a. If a certain volume is filled with spheres arranged in this manner, they will occupy 68.5 percent of the total volume. In this arrangement, therefore, the atoms fill about two thirds of the available space.

Another arrangement of atoms succeeds in filling the available space even more closely —the hexagonal close-packed arrangement. Illustration 1b shows how the atoms are arranged in such a configuration, which is generally referred to by the abbreviation hcp. In this structure the atoms fill 74.1 percent of the available space. It should be noted that many elements conform to this arrangement of the atoms in the crystal. Other elements crystallize in a different way, but they recrystallize when they become subject to exceedingly high pressures, arranging their atoms according to the hcp pattern. When the substance has recrystallized in this different form it has a much greater density.

Illustration 1c helps clarify the concept of how the atoms are arranged in the hcp lattice. The atoms are shown here in their correct relative positions, but they are represented by spheres that are drawn out of scale—smaller than they should really be.

1c



THE DIAMOND TYPE—To understand how the structure of a diamond is formed, the Bravais lattice of the face-centered cube should be used as a starting point, with consideration being given to each position to be occupied by a base consisting of two identical atoms (in the case of the diamond these will be carbon atoms). This pair of atoms is not in all cases arranged with the same orientation: in the various positions of the lattice the pair is orientated in such a way that the second atom (the first atom occupies the exact lattice position) takes up its position wherever it is possible for it to become housed in an interstitial space of suitable dimensions. This illustration shows just one cubic cell, with a total of 18 atoms—14 arranged at the corners and at the centers of the faces, and four within the body of the cube. These latter are in addition to the normal complement of a face-centered cube. It is right that there should be four other atoms completely inside the cell: for each atom placed on the lattice itself there is one (and only one) inside the cube to form the double base. The pairs are then arranged in such a way as to obtain the characteristic tetrahedron arrangement shown in a darker shade of blue in one of the corners of the cube. Carbon is not the only substance that crystallizes with the diamond structure. Silicon, germanium, and gray tin crystallize with the same structure, and so do a number of minerals.

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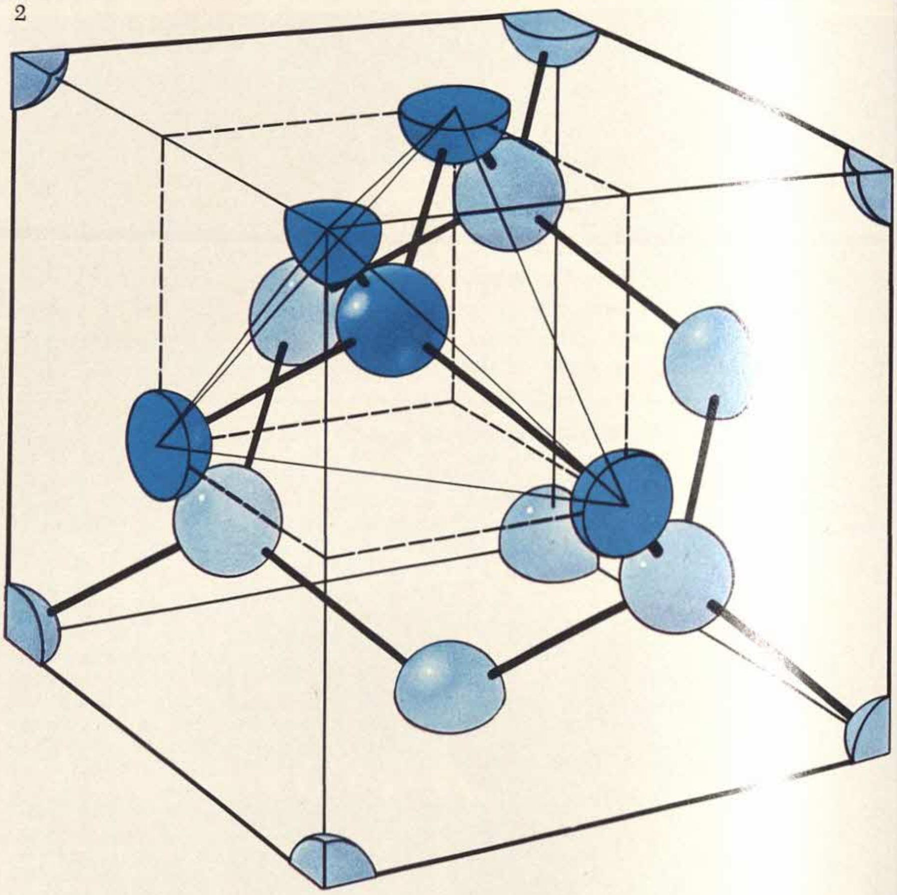

THE STRUCTURE OF SPHALERITE—Sphalerite (zinc blende) crystallizes with the same structure as the diamond, with the only difference being that the double base does not consist of two identical atoms but of two different ones, zinc and sulfur. In this illustration they are symbolically represented by yellow spheres for sulfur and gray ones for zinc. It should be noted that the structures of the diamond and of sphalerite are obtained by means of two staggered face-centered cubes, displacing them along the diagonal by one fourth of its length.

Many other crystals also possess the same structure. Among these are CuF, CuCl, AgI, ZnSe, CdS, InAs, InSb, SiC, and AlP.

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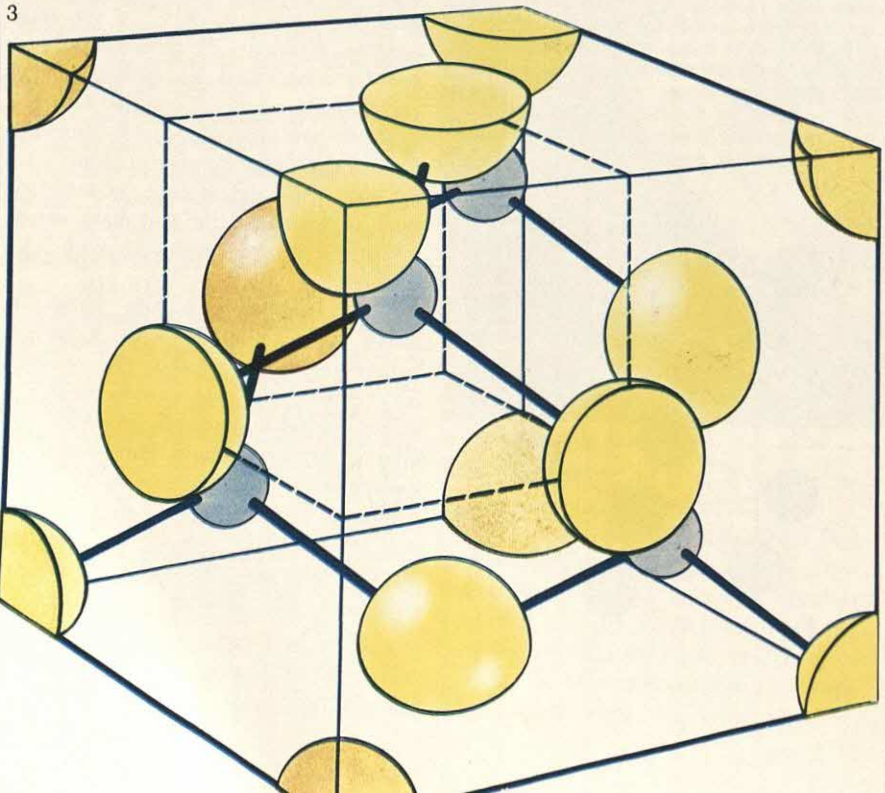
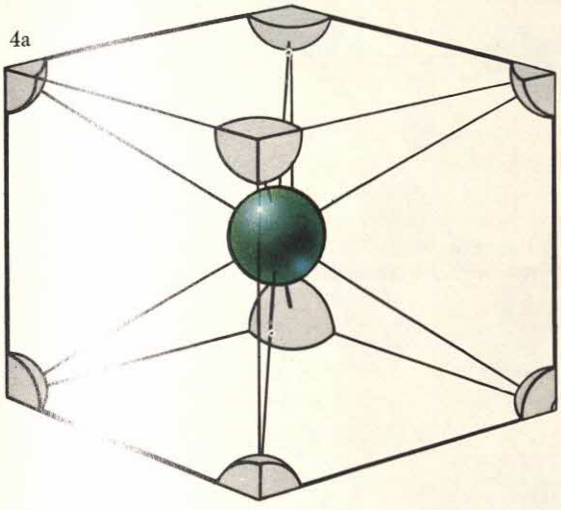
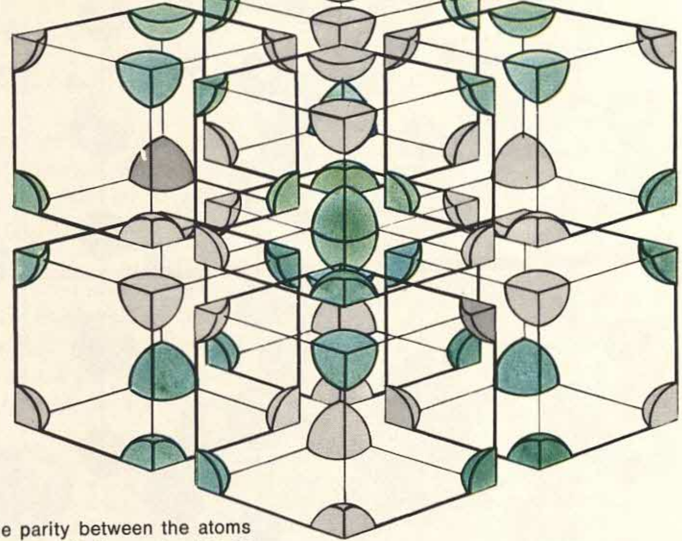


found among the organic substances, because the molecules often have large dimensions. However, these substances are not relevant to this discussion because the magnitudes that determine the properties of the aggregate depend to a far greater extent on the bonds of the various atoms that constitute the molecule than on the arrangement of the bases in the crystal lattice. The bonds that keep these very large molecules unified to form a complex crystalline solid are the product of a large number of atoms of one molecule being brought close to those of the adjacent molecules. Often these bonds are relatively weak, resulting in low fusion points. Moreover, these solids are often defective—and this characteristic, together with the weakness of the bond, produces a high degree of plasticity. Therefore, the study of the complexities of the organic substances goes beyond the immediate scope of this discussion, which is concerned with the less complex inorganic structures. Thus, this article is aimed mainly at clarifying the concepts connected with crystal structures, as a prelude to the study of the properties of imperfect crystals. In fact, the greater part of the properties of the crystals depends on their imperfections and not merely on their structures. However, before study

4a



4b



THE CHLORIDES OF CESIUM AND SODIUM—These two illustrations clarify the body-centered and the face-centered cube structures. In both cases the base consists of a pair of atoms, or a molecule of the substance. The atoms have different diameters; in these illustrations they are also distinguished by means of the color. In both cases it is quite easy to see that the parity between the atoms of the two components of the molecules is respected.

In the case of cesium chloride (Illustration 4a), this is particularly obvious because there are very few atoms: 8/8 at the corners and one at the center of the cube. The calculation is rather more complex in the case of sodium chloride (Illustration 4b), because in this case it is necessary to determine the fraction of the atom that must be counted. The illustration shows exactly how each atom is split up in order to obtain parity between the two kinds, as required by the molecule.

A STRUCTURE WITH A TRIATOMIC BASE—When the base becomes complex, the crystalline structure becomes more complicated. Nevertheless, the principles already formulated in this article make it easier to understand how even complex crystals are structured.

Fluorite has a face-centered cubic structure and a triatomic base. The illustration shows the calcium atoms in the positions on the cube and where they are also to be found in actual practice; for each calcium atom there are two fluorine atoms (fluorite is, in fact, nothing more than calcium fluoride, CaF_2). In order to determine the correctness of the ratio, it is necessary to count each atom in the lattice positions as the fraction that is due to it by virtue of its position. The calcium atoms in the illustration have not been split up on this basis, but it is quite readily seen that the ratio between calcium and fluorine is 1:2 (four calcium atoms in the lattice positions and eight fluorine atoms inside).

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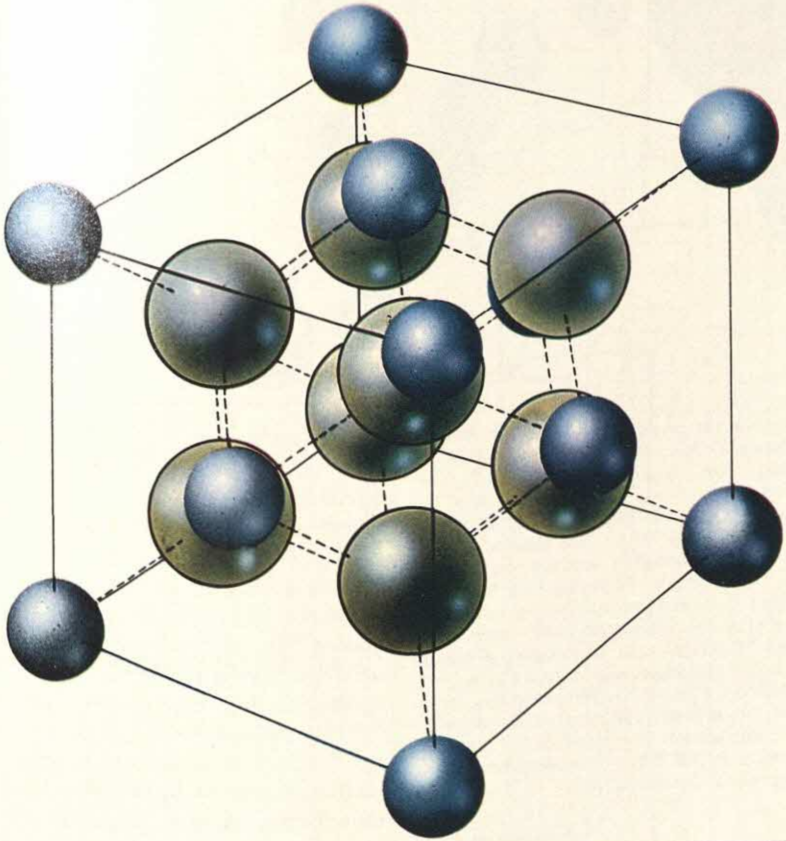


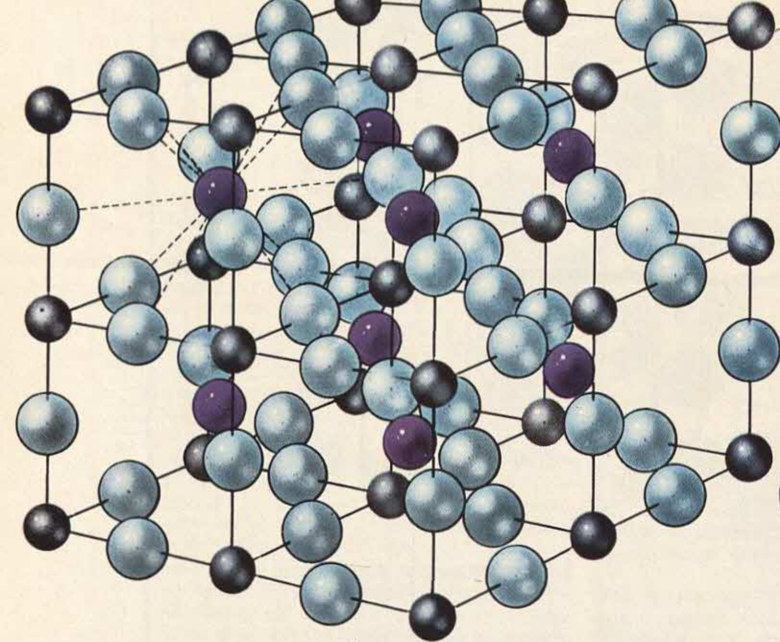
of the imperfections, it is necessary to analyze the structures of crystals as they would be if they did not contain these important characteristics.

TWO FUNDAMENTAL PRINCIPLES

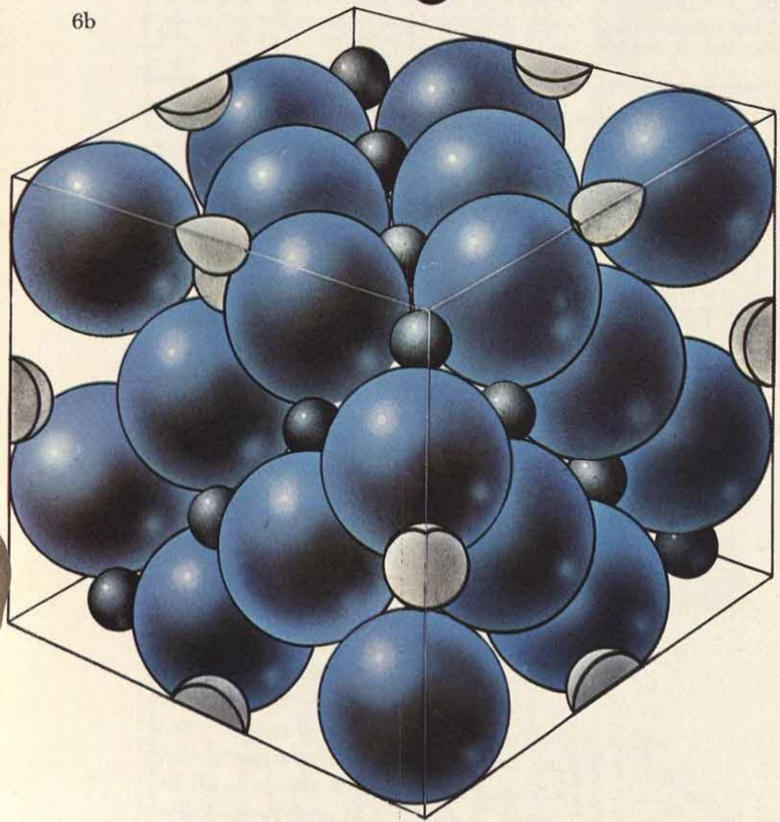
Once the concept of the crystal lattice and the concept of a base have been clarified, it is possible to understand a number of principles governing the manner in which the base arranges itself within the lattice to form the crystalline structure.

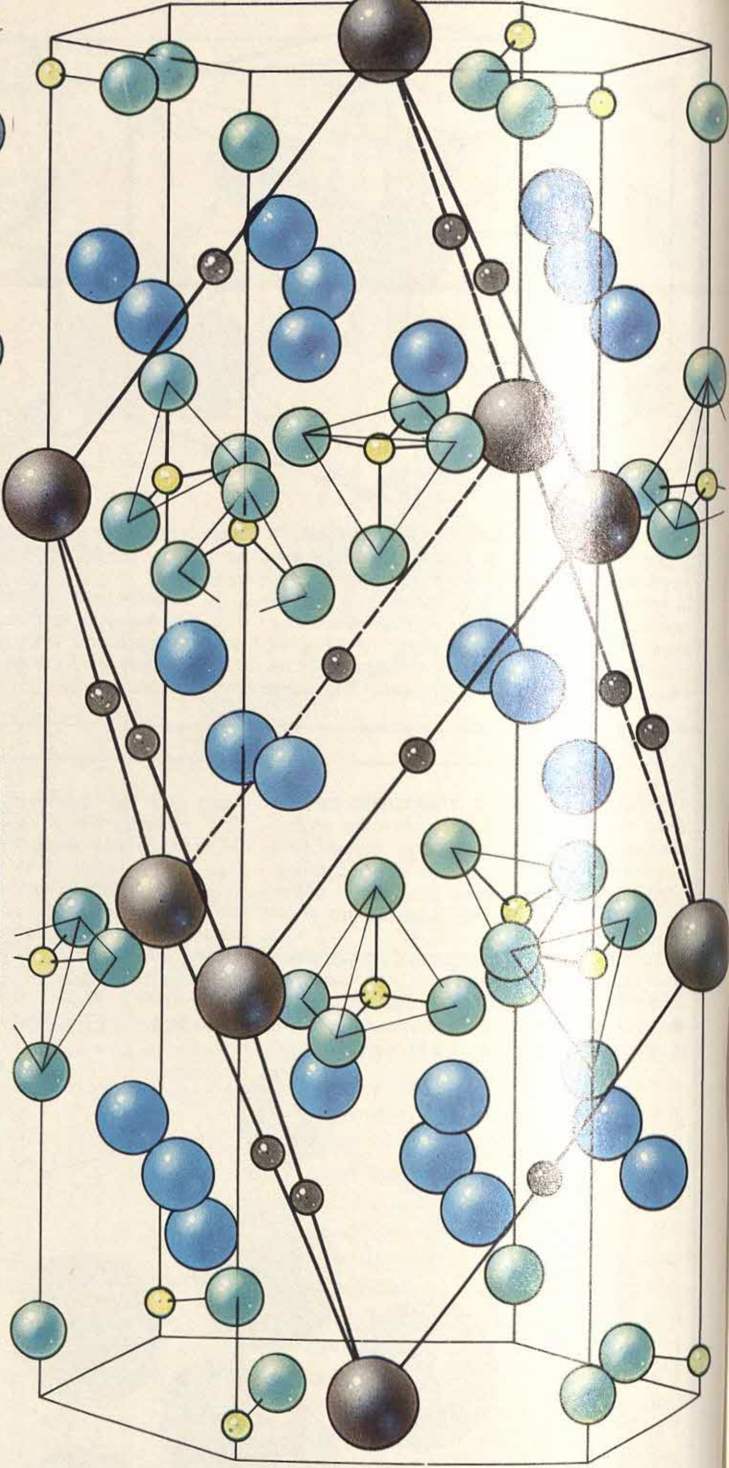
No exceptional intuition is needed to understand the principles by which the crystalline bases can arrange themselves in a lattice. The first principle is that of achieving the minimum volume. For example, imagine a model in which the molecules consist of small spheres glued together. If these spheres are placed close to each other in such a way as to fill the lattice, it does not by any means follow that a parallel arrangement will be the best one. Generally, more than one cell must be taken into consideration in order to find a periodic pattern in the structure. The bases will generally arrange themselves in such a way as to leave a minimum interstitial volume.

The second principle requires the bases to respect the orientation of their internal bonds when they come to arrange themselves close to one another. These bonds are the forces that keep the atoms of the molecule close to one another. They act along well-defined patterns, and are certainly not arranged at



6b





VERY COMPLEX STRUCTURES—These three illustrations show just how rapidly the complexity of the crystalline structure increases when the molecules serving as bases become more complex by virtue of the fact that they contain a larger number of atoms.

The first structure (Illustration 6a) is that of perovskite, the titanate of calcium ($CaTiO_3$). The base in this case is a relatively simple one, but it is, nevertheless, quite sufficient to produce crystallization in a pseudocubic orthorhombic or monoclinic lattice. The illustration shows the arrangement of several cells, making it easier to understand the arrangement of the atoms in the structure.

The greater complexity of the spinel structure shown in Illustration 6b is due to the greater number of atoms in the base; in fact, the formula for the spinel molecule is $MgAl_2O_4$. The magnesium ions, each surrounded by four oxygen atoms, occupy the vertices of the tetrahedrons; the aluminum ions, on the other hand, are located at the vertex of a tetrahedron and are surrounded by six oxygen atoms (these may be the same ones that surround the magnesium ions).

Illustration 6c shows an even more complicated structure—that of jarosite, a sulfate of iron and potassium. The formula is a complicated one, $KFe_3(SO_4)_2(OH)_6$, and the structure of the crystal, therefore, is correspondingly complicated. Nevertheless, it can be interpreted in the manner shown above. This is a ditrigonal pyramidal cell.

random. The bases, therefore, tend to take up positions that will enable the atoms to arrange themselves in a manner where the cohesive forces will be linked in the most natural way. In practice, however, the structure will be based on a compromise between the need for attaining the minimum volume and the need for having the bonds arranged according to their correct orientation.

Thus, the knowledge of the structures can be used as a starting point for extending the study in two directions: an examination of the properties of the imperfect crystals, and a study of the macroscopic crystalline forms.

THE CRYSTAL LATTICE | the discovery of the elementary cell

Sherlock Holmes would have had a fascinating time with the crystal lattice. The famed fictional detective was a wizard at making discoveries through the process of deduction. His prowess would have stood him in good stead in the study of crystals. Much of such study indicates that the atoms within crystals are arranged in some regular pattern. The goal here is to understand how these atoms are arranged, although the subject will be simplified as much as possible.

While limiting further study to the theoretical field, this article focuses on a continual development of knowledge concerning the crystalline state. At the same time, a Holmes-like effort will be made to understand how the regular patterns of the atoms can be deduced from the characteristics of the crystals.

THE FIRST HYPOTHESES ON THE CONSTITUTION OF CRYSTALS—A few centuries ago, the observation of the basic properties of crystals—especially their flaking, regular geometric form and symmetry—suggested that crystals were made up of some particularly simple geometric base elements. For example, in those times an examination of the crystal illustrated here may well have led to the belief that a cubic crystal could be made up of a large number of microscopic cubes of the same substance as the large crystal, and that the cubes were placed side by side and held together by forces weaker than the internal forces of the substance itself. This subdivision could not proceed ad infinitum, but only as far as the constituent element of the crystal structure, that is, the so-called integral molecule, whose destruction would also lead to the destruction of the chemical compound. This hypothesis on crystal structure was put forward by the French mineralogist R. J. Haüy in 1784; it reinforced the concept of the continuity of matter. At that time, in fact, it was believed that matter completely filled the space occupied in a continuous manner; discontinuities observed in the flaking and growth of crystals were simply attributed to the weak bonds that *united* the elementary portions that, it was thought, made up the crystal. Haüy thus believed that other crystals consisted of elements with forms similar to the form of the complete crystal. Later, when the atomic theory of matter was taken up again, scientists began to think that crystals, like gaseous or liquid matter, might have a discontinuous atomic structure. The atoms that took part in the combinations of the substances resulting in various types of compounds obviously had to be the same atoms that formed the crystals. The crystals could, therefore, be imagined as groupings of atoms, either in contact with each other or separated by empty spaces. However, before a clear idea of the nature of crystal lattices can be obtained, some fundamental properties of two-dimensional lattices must be examined.

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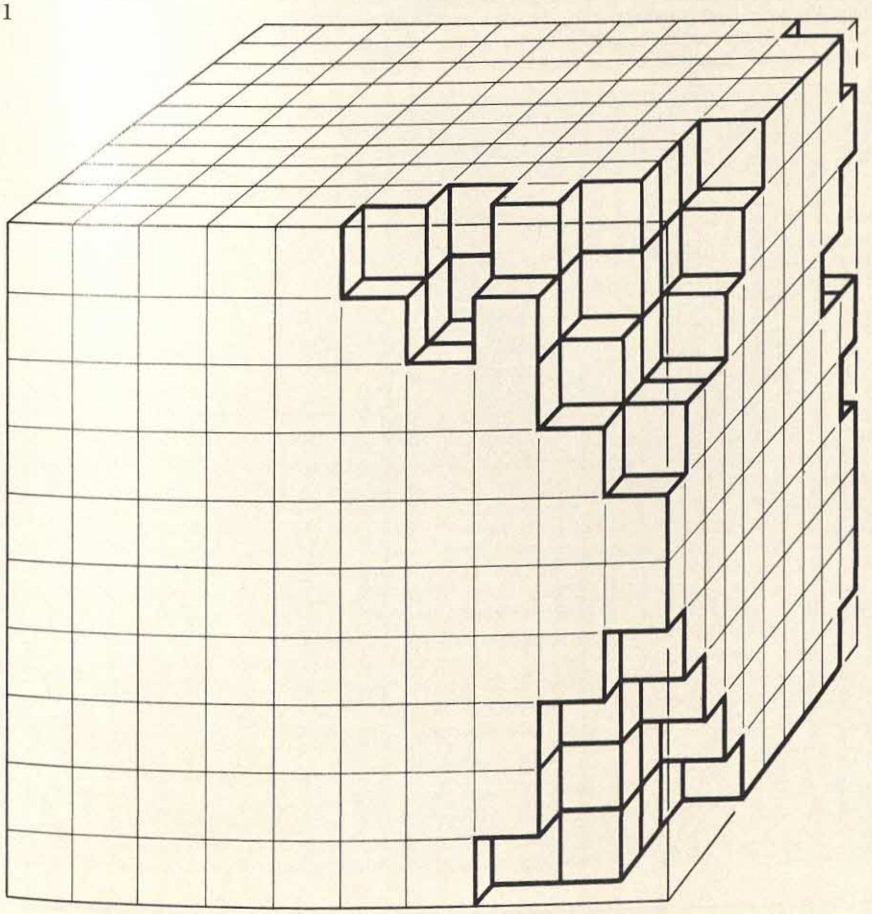
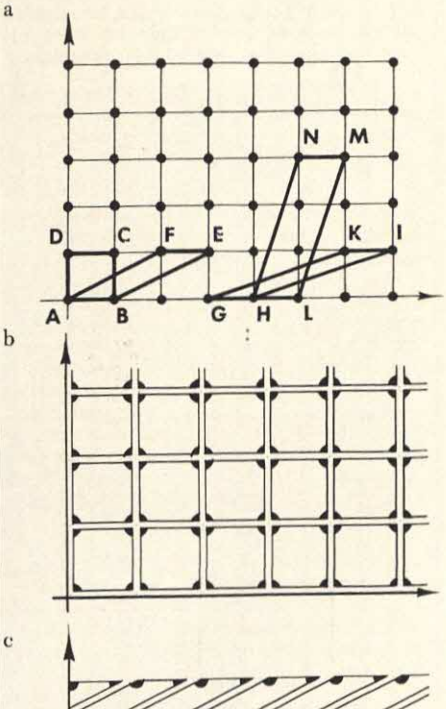


2

PLANE CRYSTAL LATTICES (GRIDS)—Illustration 2a shows the construction of a plane lattice, or grid. Two Cartesian axes are drawn; the plane defined by the axes is then subdivided into squares of equal size. At the corners of the squares, small circles are drawn to represent the positions of the atoms. The names for the parts of this grid are intuitive. (The squares could be lozenges if two non-orthogonal axes are used.) The circle points are the nodes of the grid, and each square is a mesh. One mesh, for example, is formed by *ABCD;* it is a simple square. However, a mesh can also be constituted by the points *ABEF.* This mesh is a parallelogram whose area is equal to that of the square.

An important property of the meshes is the fact that they can be used to construct a complete grid by placing them side by side. Illustration 2b shows a grid made up of a large number of square cells.

The grid can also be constructed by repeating the rhomboidal mesh (Illustration 2c). This mesh is obtained by juxtaposing rhombuses rather than squares. Other types of meshes are possible—for instance, the mesh formed by *GHIK* (Illustration 2a), which is once again rhomboidal, but longer than *ABEF.* Another mesh would be *HLMN.* This mesh not only has a larger area than the others so far described but also encloses two nodes of the grid. Of all the possible meshes, the square *ABCD* has the minimum area and the simplest form. For this reason the square is called the elementary mesh; when a grid is imagined it is conceived as being formed by elementary meshes.



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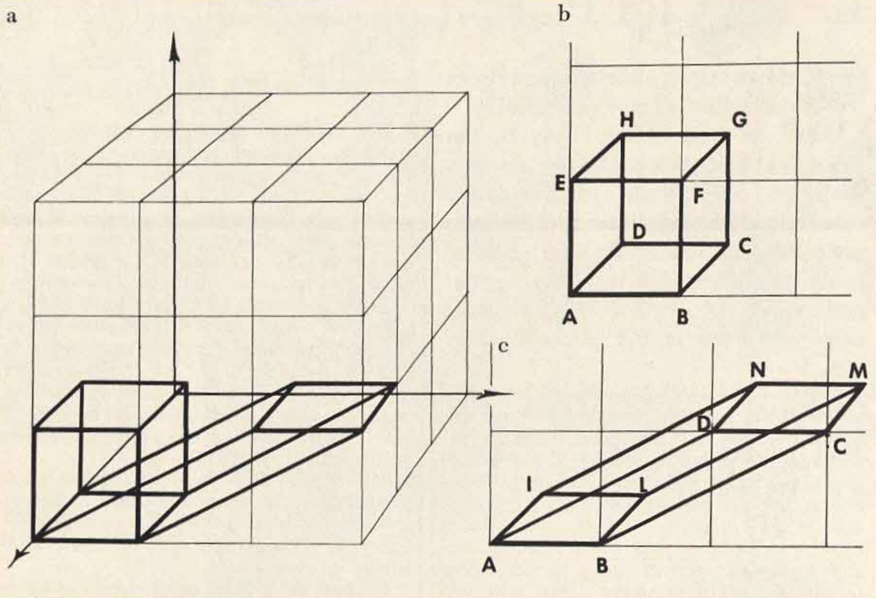


THE THREE-DIMENSIONAL LATTICE—A three-dimensional lattice (Illustration 3a) can be constructed in space using much the same method employed in forming the lattice or grid. Three orthogonal axes are constructed. The space delimited by the axes is then divided into a large number of identical and adjacent cubes.

Illustration 3b shows it is possible to find in space something that corresponds to the elementary mesh. The small cube defined by the points *ABCDEFGH* is the elementary mesh of the space lattice; it is isolated from the complete lattice. This elementary cell constitutes the fundamental element of the space lattice.

A subdivision into cells other than the elementary cell is also possible. For example, a cell can be constructed by the points *ABCDILMN* (Illustration 3c), but this cell is not so simple as the elementary cell.

4

LATTICE, BASE, AND CRYSTAL STRUCTURE—In the preceeding illustrations, it was stated for the sake of simplicity that the atoms in real solids can be found at the indicated points of a lattice or at corresponding points of more complex lattices. This is true, however, only in the case of chemical elements. A more complex formula is used in the case of compounds.

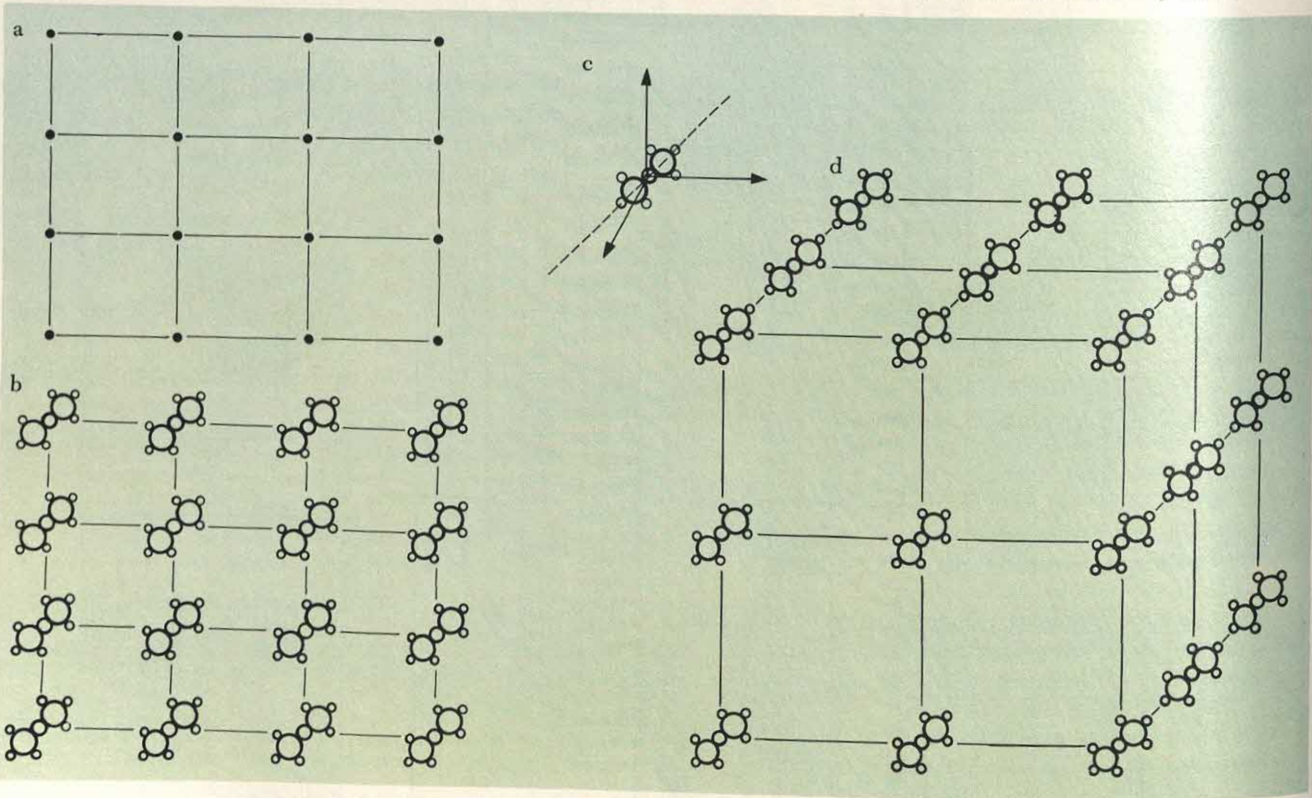
This space lattice (Illustration 4a) consists of points distributed in space. (For the sake of simplicity, only the points situated in one plane are shown.) The points mark positions that follow a regular pattern. The term *space lattices,* however, also is used for plane lattices whenever they indicate the position of the centers of the atoms that are to be found in one and the same plane.

A crystal of a substance consisting of polyatomic molecules can be perfectly described only if the respective positions of the atoms are shown in the molecules. Crystallography, in fact, defines the position the atoms assume in a molecule when arranged with others to form a crystal. This molecule is said to constitute a base, such as the one shown in Illustration 4b.

The crystalline structure of a real solid consists of an arrangement of bases at the nodes of a space lattice (Illustration 4c). In each of these points the center of gravity or the geometric center of a base can be found, and as many bases occur as there are lattice points in the whole of the crystal.

A crystal structure in three dimensions consists of an arrangement of bases at the node points of a space lattice (Illustration 4d). To give a clear picture of the arrangement of the atoms, two simplifications have been introduced. Only a small portion of the crystal has been shown, and the atoms in the bases have been reduced in size instead of being drawn to scale. The bases in the illustration, therefore, also have been made to appear much farther apart than they really are.

In real crystals the bases must be considered as spheres in contact with each other, slightly deformed where they touch.



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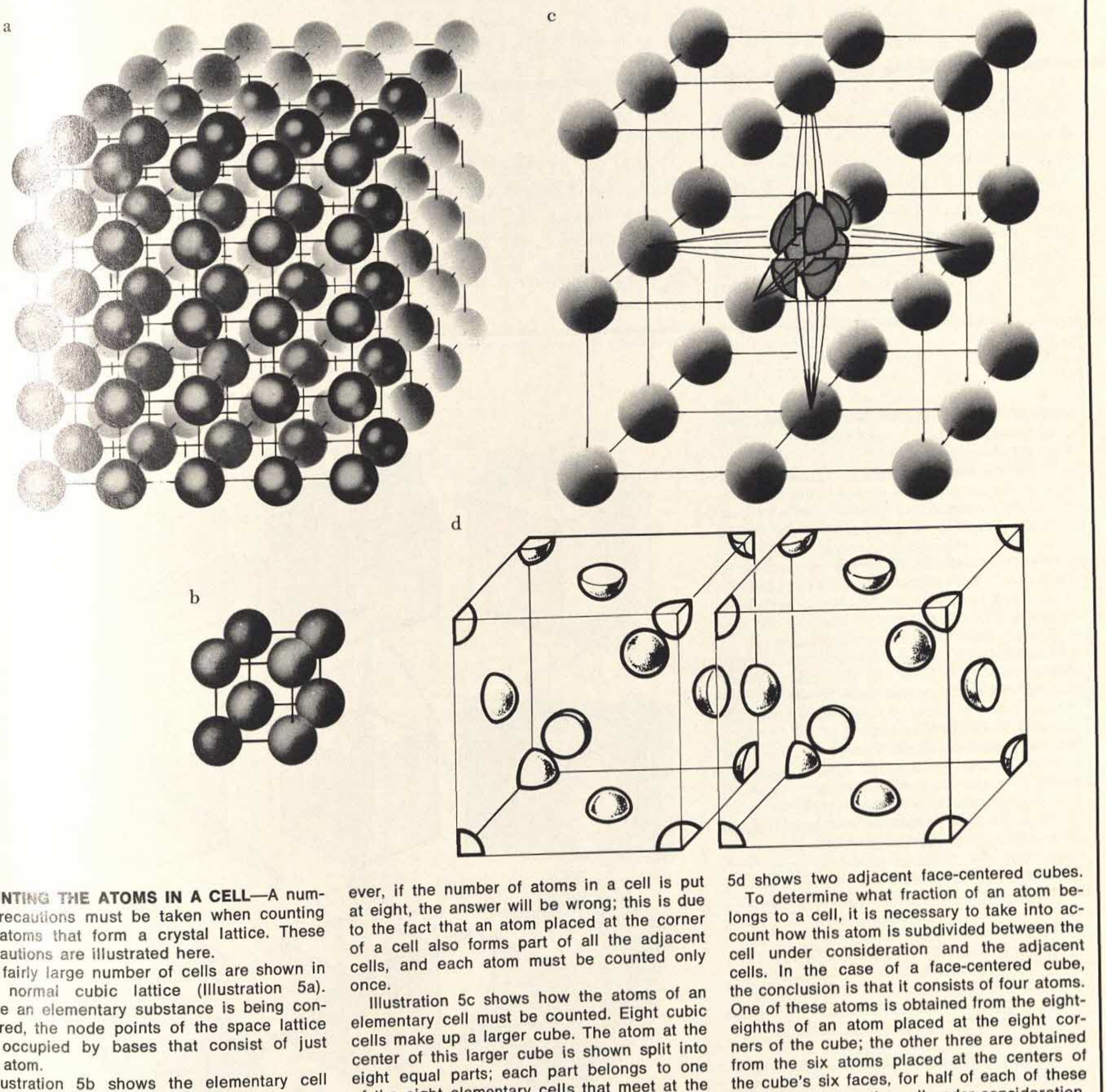


COUNTING THE ATOMS IN A CELL—A num- of precautions must be taken when counting the atoms that form a crystal lattice. These precautions are illustrated here.

A fairly large number of cells are shown in this normal cubic lattice (Illustration 5a). Since an elementary substance is being considered, the node points of the space lattice are occupied by bases that consist of just one atom.

Illustration 5b shows the elementary cell of the space lattice in the previous illustration. The cell is merely one of the many cubes that constitute the more complex structure of the complete lattice. This cube has eight atoms, one at each of its corners. Can it therefore be assumed that the elementary cell contains eight atoms of the substance? The answer is no. The crystal in Illustration 5a consists of 64 cells; the total number of atoms in the crystal should be equal to the product of the number of atoms in each cell, multiplied by the number of cells in the crystal. However, if the number of atoms in a cell is put at eight, the answer will be wrong; this is due to the fact that an atom placed at the corner of a cell also forms part of all the adjacent cells, and each atom must be counted only once.

Illustration 5c shows how the atoms of an elementary cell must be counted. Eight cubic cells make up a larger cube. The atom at the center of this larger cube is shown split into eight equal parts; each part belongs to one of the eight elementary cells that meet at the point in which the atom is situated. Since the structure being considered is made up of cubes, each elementary cell possesses only one-eighth of an atom at each of its corners. The number of atoms belonging to the elementary cell is, therefore, made up of eight-eighths of an atom; that is, one-eighth of an atom at each of the eight corners of the cube.

In the case of a face-centered cube, the atoms situated at the centers of the faces belong to only two adjacent cells. Illustration 5d shows two adjacent face-centered cubes.

To determine what fraction of an atom belongs to a cell, it is necessary to take into account how this atom is subdivided between the cell under consideration and the adjacent cells. In the case of a face-centered cube, the conclusion is that it consists of four atoms. One of these atoms is obtained from the eight-eighths of an atom placed at the eight corners of the cube; the other three are obtained from the six atoms placed at the centers of the cube's six faces, for half of each of these atoms belongs to the cell under consideration, while the other half belong to the adjacent cell.

Analogously, it can be seen that a body-centered cube consists of only two atoms. Once again, there are the eight-eighths of an atom at the eight corners of the cube, plus one atom at the center. This central atom does not have to be subdivided and shared with adjacent cells because it is completely separated from them.

BRAVAIS SPACE LATTICES | the microcosm of crystal structures

The atoms forming crystalline solids—solids that include practically all metals, minerals, and alloys—are arranged in simple and regular patterns called crystal lattices. The starting point of the study of crystallography is the analysis of the rare types of symmetry of crystal lattices, for many of the laws of crystallography depend on simple properties of the geometry of symmetrical movements. Imagine having to cover a pavement with a mosaic of small tiles. The tiles must be placed in perfect contact with each other, without leaving any spaces or without splitting any tiles. The number of possible combinations will depend on the elements of symmetry of the tiles. While crystal lattices are more complex than tiles—the unit cells being three-dimensional rather than two-dimensional—the analogy is nevertheless a useful one.

There are 14 basic types of crystal lattices, called Bravais space lattices after Auguste Bravais, the nineteenth-century French physicist who first gave a complete description and classification of these structures.

CRYSTALLOGRAPHY AND THE THEORY OF GROUPS

Crystallography employs one of the most advanced branches of mathematics, the theory of groups. In order to visualize better what is involved in this theory, imagine a cube placed on a table so that its sides are parallel to the sides of the tabletop. Considering only the geometric figure of the cube, it is obvious that the cube can be rotated through 90°, 180°, or 270° and still occupy the same space it did at the beginning. Such changes in

1

SYMMETRIES OF THE CUBE—The operations of symmetry to which a cube may be subjected are as follows:

Three planes of symmetry parallel to the face of the cube can be drawn (Illustration Ia). To better visualize this phenomenon, imagine a mirror placed in the plane. The mirror image of one half of the cube will correspond exactly to the other half. No other planes parallel to the faces of the cube exist in this situation.

As many as six diagonal planes of symmetry can be drawn (Illustration 1b). Each plane has a different orientation from the others.

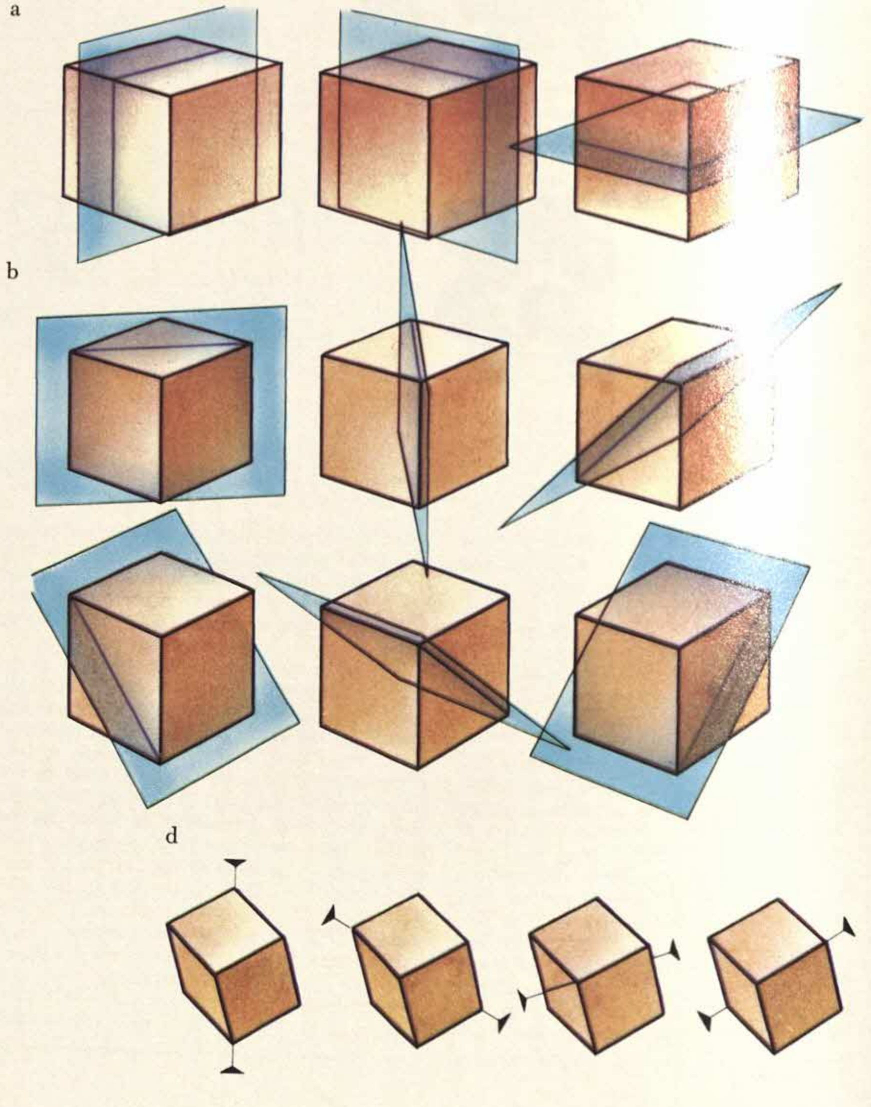
Illustration 1c shows the three axes of symmetry of a cube. Each of the axes passing through the center of the cube is perpendicular to the two faces it crosses. The small squares at the ends of each axis indicate that the cube can be rotated through 90° and still occupy the same original space. Because there are four such rotations in a full turn, this type of axis is known as quaternary.

The cube also possesses four ternary axes of symmetry, represented in Illustration 1d by segments. The triangles at the ends of each axis indicate that three rotations of 120° can be made about these axes, each of which will leave the cube occupying exactly the same space as before.

Illustration 1e shows six binary axes of symmetry. Two rotations of 180° can be made, each of which brings the cube back to its original position. The extremities of these axes are therefore marked with a symbol having two points.

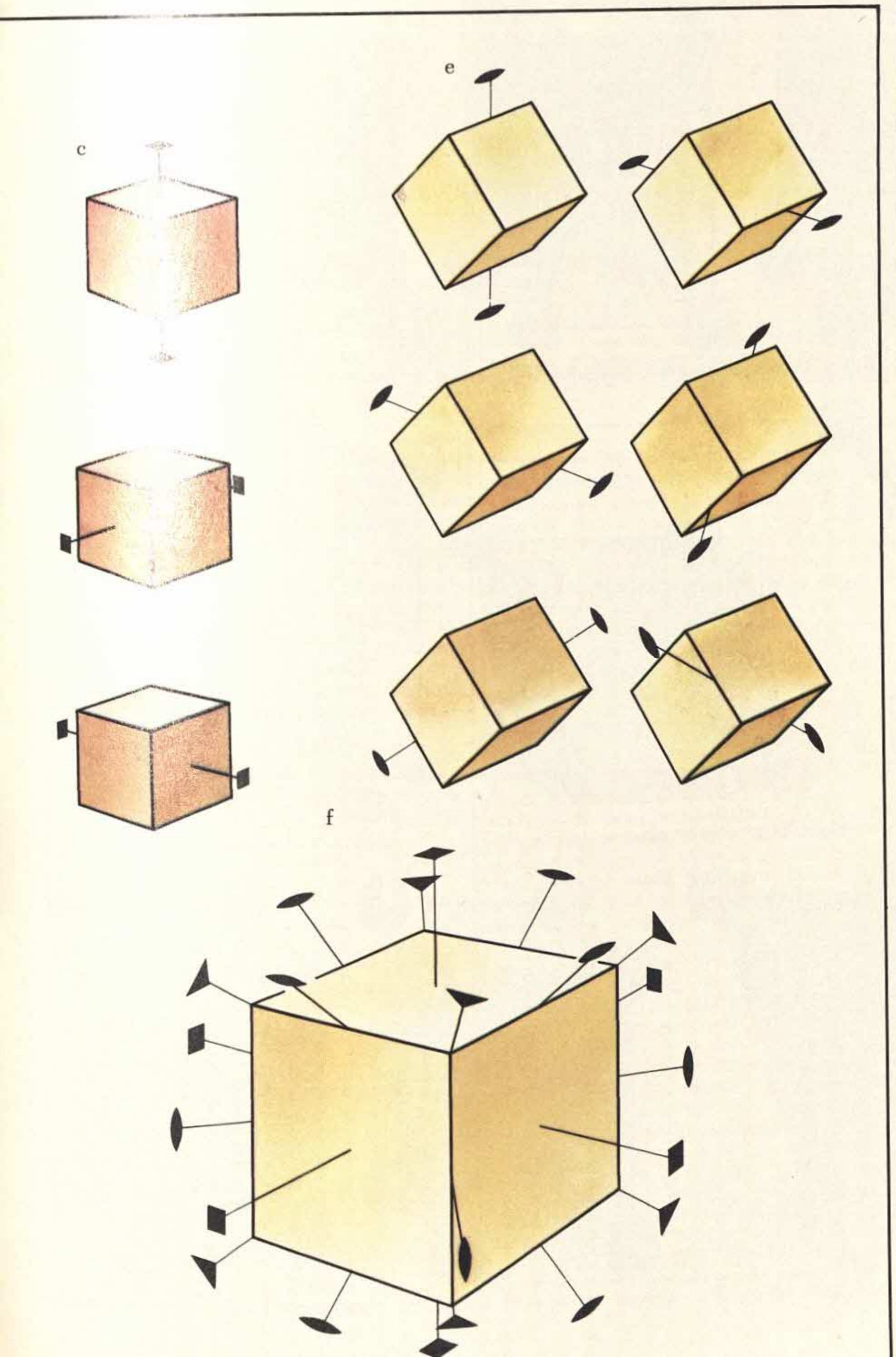
Illustration 1f shows all the axes of symmetry that a cube may have. Each axis is marked to indicate its type: binary, ternary, or quaternary.

A cube has a center of symmetry. A polyhedron has a center of symmetry when all the straight lines joining opposite equivalent elements pass through the same point, and when each such line is bisected by that point.



the position of the cube are known as operations. Rotations are only one of the operations that can be performed to change the orientation of the cube without changing the position of its corners and faces with respect to the table on which it rests. The total operations that can be performed constitute a group. The number of operations in a group may be limited or unlimited.

If certain operations are to form a group, the successive application of two operations must lead to a result that can also be obtained by the application of some other operation of the group or, alternately, by the application of several other operations of the group. The rotation of a cube through 180°, for example, can also be obtained by two successive rotations through 90°; thus, the application of these two successive operations leads to the same result as the application of the first operation. This restrictive condition ensures certain groups consisting of a finite number of operations, while other groups may be made up of an infinite number of such operations.



THE 14 BRAVAIS SPACE LATTICES—The number of ways in which the bases of crystalline structures can arrange themselves to form cells is limited to 14 (see p. 100). Identification of each cell is given below.

The crystallographic symbol of the simple cubic lattice (Illustration 2a) is Cube P (for "primitive"). Its dimensions are determined by the length of one of its three identical sides. Three coordinate axes originate at the corner of the cube marked by the arrow.

A variation of the simple cube is the body-centered cubic lattice (Illustration 2b), called Cube I. Because the additional base is at the geometrical center, the outline of the cell is unchanged. Its dimensions are determined by the length of one of the sides.

The face-centered cubic lattice (Illustration 2c) is known as Cube F. Its dimensions can be determined by the length of one of the three fundamental sides, because side a = side b = side c.

The simple orthorhombic lattice—Orthorhombic P (Illustration 2d)—is composed of three unequal sides: a, b, and c. The lengths of all three sides must, therefore, be determined in order to identify the cell. Because the three sides are perpendicular to each other, it is not necessary to specify the angles between them.

The base-centered orthorhombic lattice—Orthorhombic C (Illustration 2e)—has an additional atom or molecule at the center of its base and top.

The body-centered orthorhombic lattice—Orthorhombic I (Illustration 2f)—has an additional base at the center of the body.

The face-centered orthorhombic lattice—Orthorhombic F (Illustration 2g)—has an additional atom or molecule at the center of all the faces—base, top, and sides. The basic, or primitive, structure in each class is always characterized by the letter P; the base-centered variant by the letter C; the face-centered variant by the letter F; and body-centered variant by the letter I.

The simple triclinic lattice (Illustration 2h) is characterized by the letter P; however, its three sides are of different lengths, and the three angles also differ. Six numerical values are, therefore, involved in its description.

The trigonal or rhombohedric lattice (Illustration 2i) is known alternately as Trigonal R and Rhombohedric R. While the sides and angles are equal, the angles are not right angles and must, therefore, have a value of less than 120°.

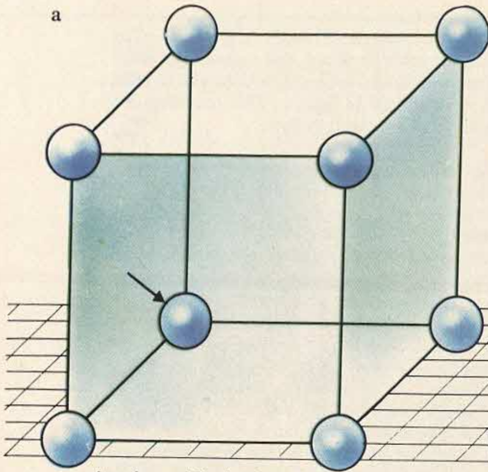
The base of the simple hexagonal lattice—Hexagonal P (Illustration 2j)—always consists of a regular hexagon. To describe this cell, the length of a side of the base and the height must be known. The Hexagonal P may be a complete hexagonal prism, or a prism on a rhomboidal base as shown in the illustration, which constitutes one third of the complete structure.

The simple monoclinic lattice—Monoclinic P (Illustration 2k)—has three different sides. The base is rectangular, and the cell takes the form of an oblique prism; it is, therefore, necessary to specify the length of the three sides and the angle of inclination.

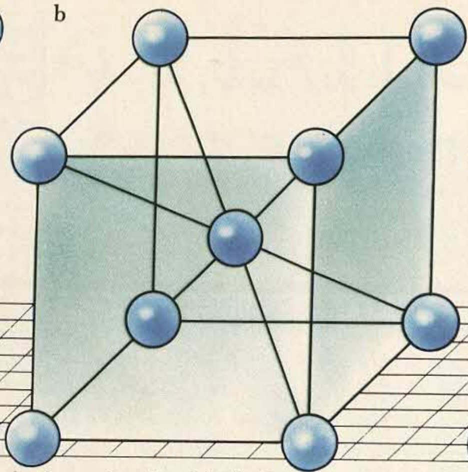
Monoclinic C (Illustration 2l)—the base-centered variant of the monoclinic lattice—is described by specifying the same elements as for Monoclinic P.

The simple tetragonal lattice—Tetragonal P (Illustration 2m)—is an orthogonal prism on a square base. Its dimensions are determined by the length of the side of the base square with the height.

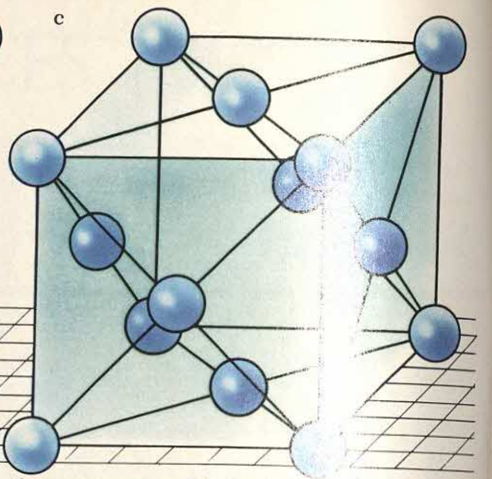
The Tetragonal I (Illustration 2n) is the base-centered variant of the tetragonal lattice. Its dimensions are determined by figuring the length of the side of the base square with the height.



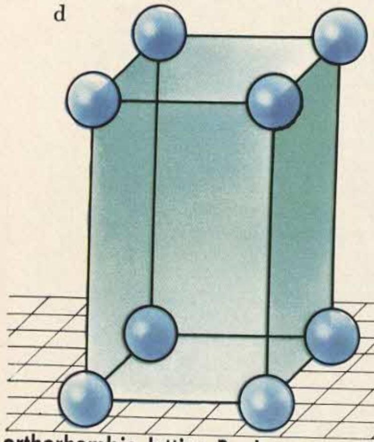
simple cubic lattice P



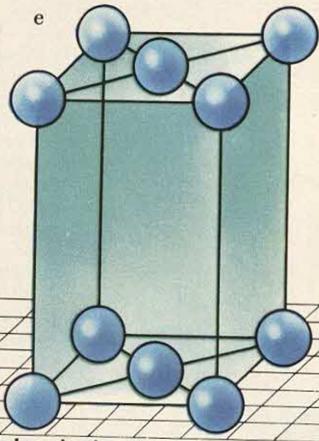
body-centered cubic lattice I



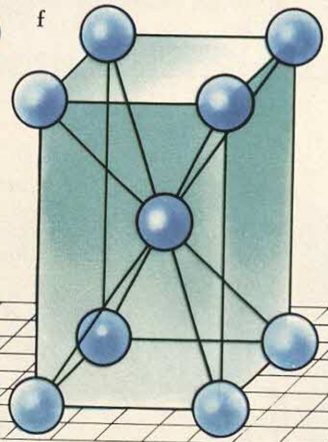
face-centered cubic lattice F



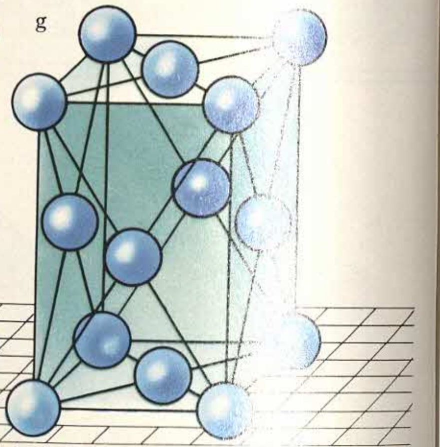
orthorhombic lattice P



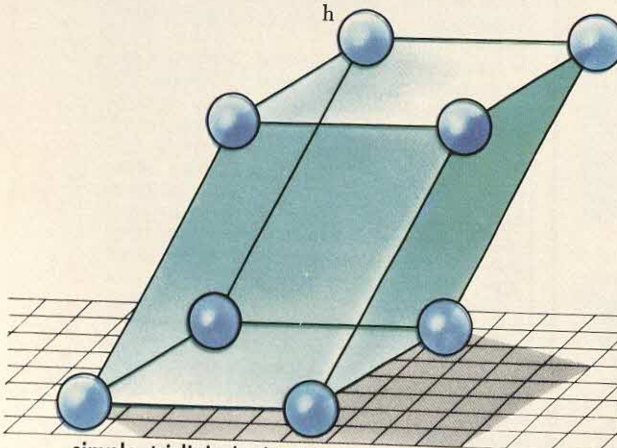
base-centered orthorhombic lattice C



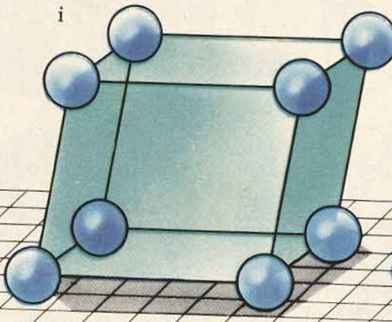
body-centered orthorhombic lattice I



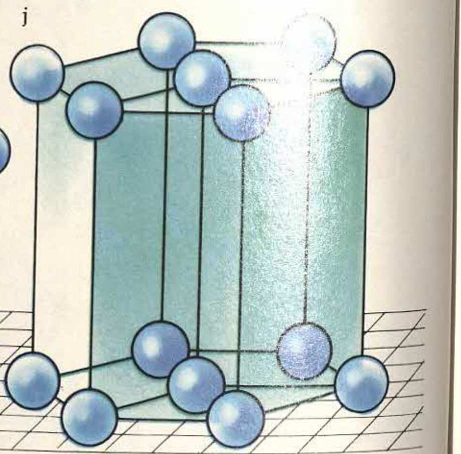
face-centered orthorhombic lattice F



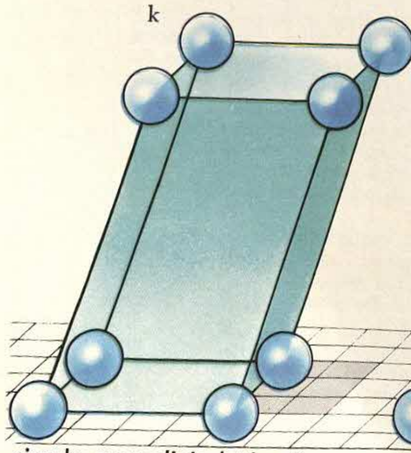
simple triclinic lattice P



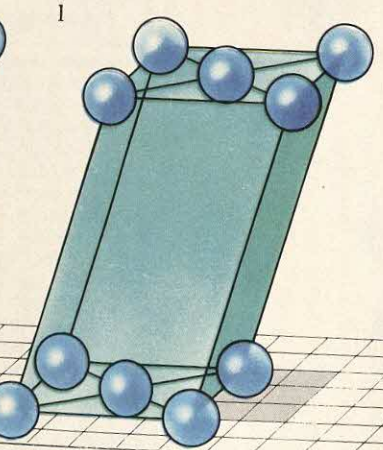
trigonal or rhombohedric lattice R



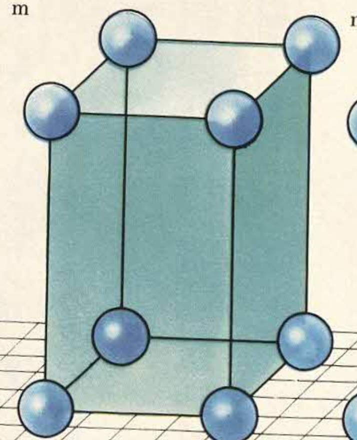
simple hexagonal lattice P



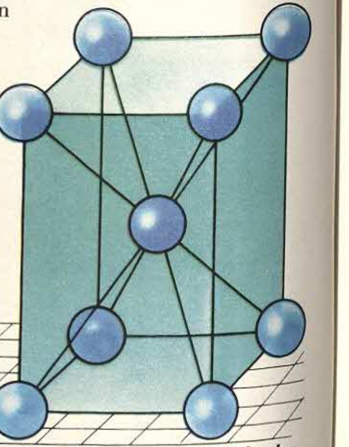
simple monoclinic lattice P



base-centered monoclinic lattice P



simple tetragonal lattice P

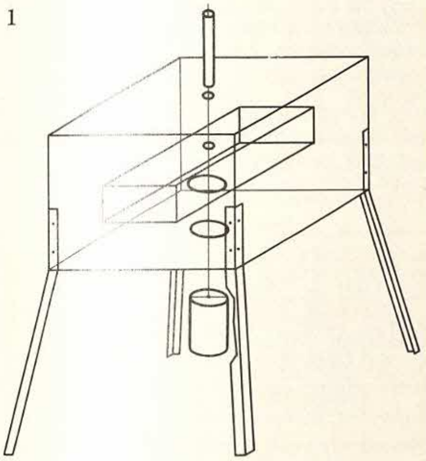


body-centered tetragonal lattice

SOLIDIFYING THE MONOCRYSTAL

from powder to perfect structure

1



THE APPARATUS NEEDED—In order to obtain monocrystals from fused materials, an electric furnace is essential. However, a number of modifications are necessary before the furnace can be used as part of the Bridgman method of growing monocrystals. This method consists of filling a crucible with the substance to be crystallized, and then passing it slowly through the furnace, first through the hot part where the material fuses, and then through the cold part where crystallization takes place.

As for modifications of the furnace, a hole must be made in the roof of the heated chamber so that it has access to the outside. Holes must be drilled through three materials: (1) the refractory lining of the roof of the heated chamber; (2) the filling of refractory earth with which it is surrounded; and (3) the outer aluminum shell. The hole through the refractory powder must be protected so that it will not close; it can be lined with a small asbestos tube folded back onto itself or with damp refractory earth left to dry; this earth will be baked hard as soon as the furnace is switched on.

The diameter of the tube must be rather small, about 5 mm (about 0.2 in.).

The lower part of the furnace also must be opened, but this opening should be larger than the one made in the roof, for the crucible must be able to pass through it. The diameter of the hole should be about 5 cm (about 2 in.), and again, the hole must be lined, especially at the point where it passes through the loose refractory earth; an asbestos tube can be used.

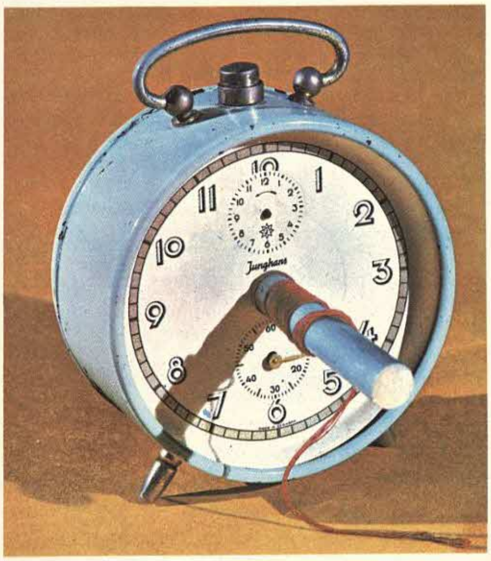
The lower part of the furnace can be provided with a shutter made from asbestos sheeting; the provisional shutter will be discarded every time the furnace is opened.

2

THE MECHANISM CONTROLLING THE MOVEMENT OF THE CRUCIBLE—In the Bridgman method, the crucible is made so that it descends from the hot to the cold part of the furnace. This is necessary because the material fuses in the hot area and then solidifies in the cold area. The descent must take place very slowly; the speed, for example, may be as slow as 1 m (about 3 ft) in 12 hours. The exact speed, however, is determined by the nature of each particular experiment. The problem here is how to obtain such a slow movement.

An old alarm clock with either a spring winding or an electrical movement is used. The shaft of the minute hand is extended; on this extension a pulley of suitable diameter is mounted. The pulley sustains a flexible cable (such as a piece of string) to which the supporting frame of the crucible is attached. Since the shaft of the minute hand makes one complete revolution per hour, the speed of the descent of the crucible depends on the diameter of the pulley attached to the shaft; for example, if the pulley has a diameter of 3 cm (about 1 in.), the descent will take place at a speed of about 10 cm (about 4 in.) per hour. However, since the clock mechanism is incapable of developing much torque, the weight of the crucible may be partly compensated for by attaching a suitable counterweight to the other side of the pulley.

The illustration shows the clock arrangement without the counterweight.

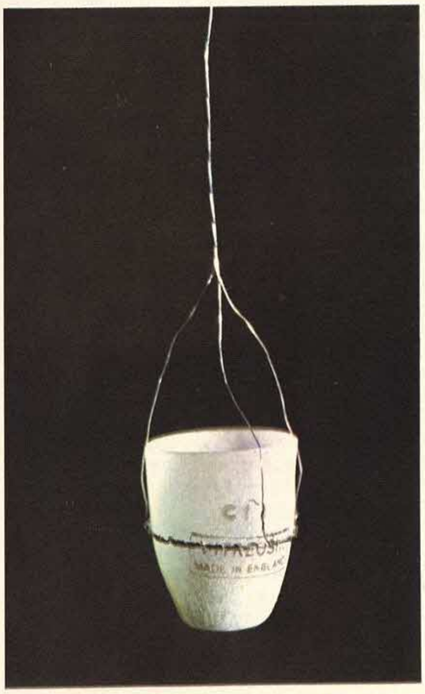


THE CRUCIBLE AND ITS SUPPORT—The choice of the crucible is important to the success of the experiment. The ideal crucible would be made of platinum, which is far too costly for a demonstrative experiment. However, a nickel crucible is more than sufficient for the materials being used in this particular case. It is essential that the crucible have very thin walls. The salt will adhere to the walls but will shrink when it solidifies. The metal also will shrink, but in a different manner, and if the walls are not thin enough the crystal may break. Quartz is also an excellent material for this experiment, but it, too, is rather costly and it may crack when solidification takes place.

Porcelain can also be used for the crucible. It has the advantage of costing little, but has a disadvantage: the vitreous part of its surface will fuse during the fusion of many substances and thus become mixed with the substance being crystallized.

Another important factor is the form of the crucible. Its bottom should come to a point, because this point will be the first part of the crucible to reach the cold part of the furnace; therefore, the first solid will form there. Since there is little space in the point where the crystal germ comes into being, this germ will consist of a single crystal. As the crucible descends, the germ will extend so that the whole mass, when it solidifies, will become united to it with only a single orientation of the lattice layers. In this way a monocrystal will be produced. Although not preferred, a flat-bottomed crucible can also be used. A cradle to support the crucible can be fashioned from the kind of nickel-chrome wire used in the resistances of the electric furnace. An eyelet at the top of the cradle can be hooked into another eyelet in the nickel-chrome wire attached to the clock movement. Illustrated is the crucible in its cradle.

3



4a

4b

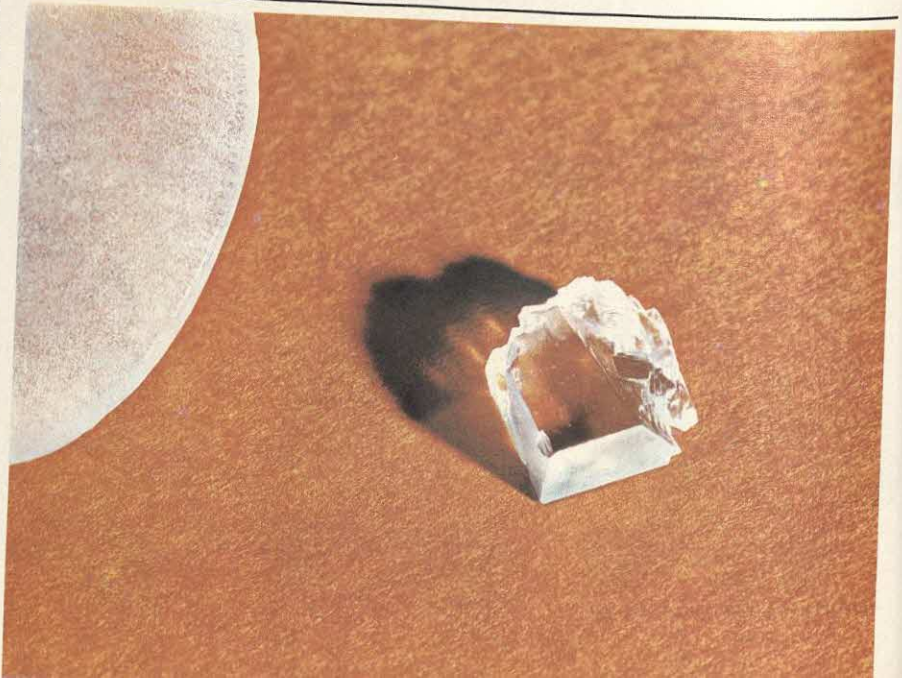
MAKING THE MONOCRYSTAL—Sodium chloride is placed into the crucible. Since it is a powder, it may be advisable to put a little more than is necessary in the crucible in order to fill it. The material must have a high degree of purity; ordinary kitchen salt is not pure enough for making monocrystals. The ideal material is the pure chloride used as a chemical reagent, but refined kitchen salt may be used if all the other sea salts have been removed. In Illustration 4a the crucible is ready for the furnace.

As shown in Illustration 4b, the crucible is placed into the furnace. To avoid burned fingers, it is best to load the furnace before turning on the heat. Quite a long time is required for the furnace to reach the temperature needed, which in this case must be above the fusion point of sodium chloride, 801° C (about 1,474° F). If the salt does not fuse, the heat should be increased (by shortening the resistance a bit, for example). Even after the fusion temperature has been attained, it still will be necessary to wait for some time to make certain that all the salt has become fused. At this point the descent is begun, using the clock mechanism. When the rotation of the reference mark, previously made on the pulley, indicates that the crucible has descended the desired distance, the furnace is switched off to begin the cooling process; also, the descent of the crucible is stopped. The crucible, with its already formed crystal, will thus cool slowly. Rapid cooling could crack the crystal.

The medieval alchemist was regarded as a magician who could change baser metals into gold or silver. Today's counterpart of the alchemist, the metallurgist, has plumbed the secrets surrounding the production of monocrystals (single crystals). In fact, a great many technical developments in today's industrial civilization are based on the possibility of obtaining monocrystals of all the elements and substances. The manufacture of transistors and integrated circuits, for example, is entirely dependent on the possibility of obtaining monocrystals of certain semiconductor substances. Again, metallurgy calls for the study of the properties of monocrystals of many metallic elements. And optics, as well as other modern techniques, requires the use of monocrystalline substances as transparent materials. However, techniques, processes, and results vary. Monocrystals of rock alum, a substance that is soluble in water and easily purified, can be readily obtained. However, most substances needed in pure and monocrystalline form do not lend themselves well to production from a solution. In fact, some of the monocrystals obtained from solutions have properties that make them quite useless for all practical purposes.

Sodium chloride, for example, has the property of being very transparent to near and intermediate infrared radiation, up to about 15 μm (microns). It is extremely difficult to obtain transparent and perfect crystals from a liquid; when such crystals must be used in experiments on the crystalline state, their imperfections all but cancel out their usefulness.

In certain respects it is simpler to grow crystals from fused substances than from a solution. A solution tends to be less stable, particularly from a thermal point of view; many precautions must be taken to make sure a continuous growth of perfect crystals takes place. Growing a crystal from fused materials may call for such equipment as an electric furnace. However, the necessary equipment is not excessively complex, and the experimental technique is fairly simple. The process for producing a monocrystal of sodium chloride will be shown here. This substance can be very useful for carrying out experiments on infrared radiation. Actually, the same method can be used with potassium chloride and other salts that have close to the same fusion point, because temperatures of less than 1,000° C (1,832° F) can be obtained quite easily in an electric furnace. The key difficulty in working with substances that have a higher fusion point is that the fusion crucible must be made of a highly refractory substance, such as porcelain.



5

THE MONOCRYSTAL—The shutter at the bottom of the furnace is opened and the monocrystal comes into view. Many mishaps may have occurred during the experiment; for example, the crucible may have cracked and the material may have spilled over the floor of the furnace, or the material may not have fused. The monocrystal may have formed, but the thermal contractions that take place during the cooling process may have shattered it in the crucible. Also, if the original material was not sufficiently pure, or if the crucible was allowed to descend too rapidly, a polycrystalline aggregate may have formed in the crucible. If, on the other hand, the monocrystal has formed, a vitreous transparent mass will be visible in the crucible.There may be a straight, flat crack, but such a crack will prove that this is indeed a monocrystal experiment. There is no point in examining the crystal to discover some type of microscopic disorder or to see whether it is only an association of almost exactly oriented crystals with parallel axes.

It is better just to break the crucible (if it has not cracked during the experiment) and to verify that the crystal can be flaked along planes, much the same as potassium chloride.

DISLOCATIONS

the imperfect geometry of crystal lattices

If Humpty Dumpty were a crystal, the question of why his various parts could not be brought together perfectly again could be answered in one word: dislocations. More specifically, dislocations are the rearrangement of the atoms on either side of each fracture.

The defects that may be present in a crystal lattice can be broadly classified into two categories. In both, the defects cause the crystal to assume properties different from those that can be deduced from the theory of the perfect lattice. The first type of defect concerns an absence or excess of atoms or ions in the crystal. Defects of this type may be associated with an excess or insufficiency of electric charge.

The second type of crystalline defect is classified under the generic name of dislocations because these defects are essentially concerned with the imperfect juxtaposition of parts of the crystal. A perfect crystal can be considered as a series of atoms arranged in accordance with the geometry of the lattice, that is, with a module regularly repeated along the whole of the crystal structure. If, however, the perfect crystal is broken into parts along a chosen plane, and if the atoms on either side of the plane of fracture are slightly rearranged, the two parts of the crystal will no longer fit together as precisely as they did before. The atoms on the two sides of the plane of fracture will no longer be in the correct positions to form perfect lattice cells. This type of defect is called a dislocation.

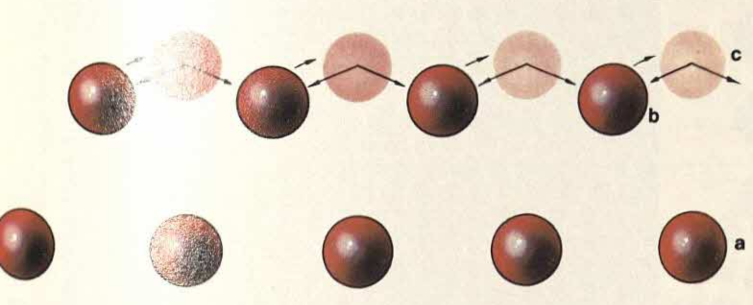
Dislocations exercise a great influence on the properties of a crystal; in metals, for example, they govern plasticity. Also, dislocations determine a crystal's growth rate. A crystal devoid of dislocations grows at a much slower rate than the same crystal with dislocations; also, the ratio between the two rates of growth may be of the order of thousands.

Dislocations, therefore, invite a large number of experimental as well as theoretical studies. The experimental study of dislocations is greatly favored by the fact that they generally affect very long rows of atoms.

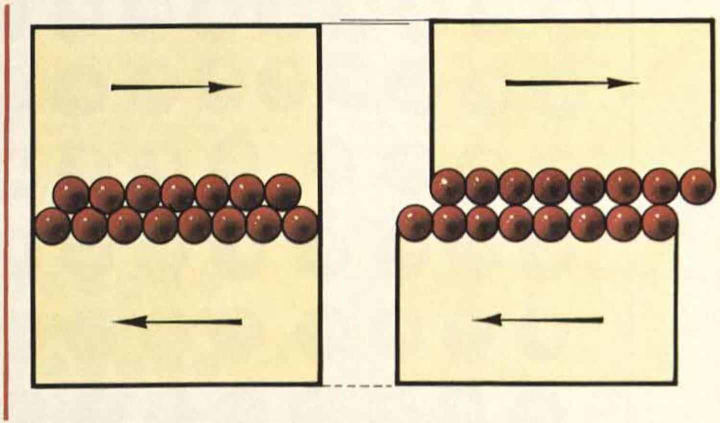
Just as dislocations represent areas where crystal growth can occur more easily, they also create zones where the crystal surface is more liable to chemical attack. If, therefore, the presence of a dislocation is to be demonstrated, no more need be done than polish a crystal's surface and subject it to chemical attack. The dislocations will then become visible even under an optical microscope. A more detailed observation of these defects requires the use of an electron microscope and the technique of repetitions.

Here the dislocations will be described from an essentially crystallographic point of view without going into the importance of the defects in determining some of the properties of the crystals.

1a



1b



SHEAR STRESS IN A PERFECT CRYSTAL—In a perfect crystal it is quite easy to calculate the force that will be needed to produce shear. Illustration 1a, which is a simplified two-dimensional model of the structure of the crystal, shows how two adjacent rows of atoms, **a** and **b**, are arranged. If the aim is to displace the upper row of atoms with respect to the lower row, the atoms in the upper row will have to be displaced in such a way that they will, at least momentarily, arrive in the position of row **c**. In order to arrive in this position, however, the atoms in row **b** must be pulled away from those in row **a**. To obtain this effect, force must be applied.

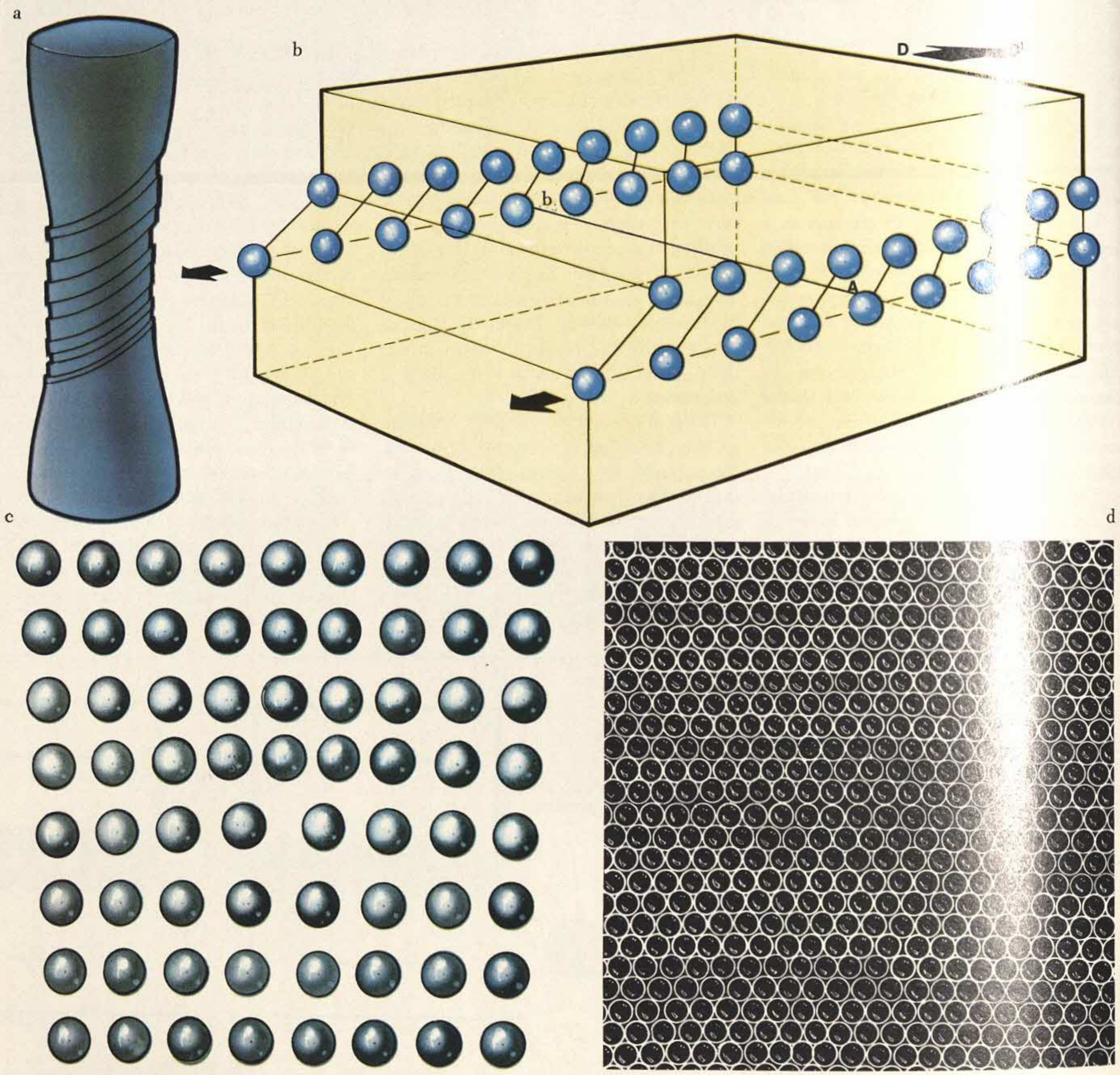
Once these atoms have arrived in position **c**, they find themselves in a state of equilibrium and they could, therefore, either return to their original position or move forward to the next interatomic position. The force needed to lift the atoms into position **c** is quite considerable.

Smaller movements—that is, movements that will bring the atoms of row **b** toward row **c** but without reaching it—give rise to elastic deformations. In fact, the atoms return to their original position as soon as the force which caused them to become displaced is removed. If the goal is to calculate the value of the elastic limit (the point where the applied force will produce a permanent, or plastic, deformation rather than an elastic one), it is necessary to obtain shear forces greater than the ones that can be measured when real crystals are plastically deformed. This means the causes that bring about plastic deformation in real (or imperfect) crystals must be different from the ones represented in this illustration, which is entirely based on the hypothesis of a perfect crystal.

Deformation by shear, at least according to the model of the perfect crystal, should occur as indicated in Illustration 1b. If a force like the one indicated by the arrows is applied, the upper part of the crystal will be lifted into the second position. In this position the two parts of the crystal have been displaced relative to each other. Also, as observation of the upper edge of the crystal discloses, they have been pulled slightly apart.

This model actually does not correspond to reality. In fact, it is sufficient to consider that plastic deformation in aluminum occurs at a stress as much as 60,000 times less than the stress needed for elastic deformation. In many other materials the plastic deformation occurs at analogously lower values than those needed for elastic deformation. On the other hand, for other materials the limit of plastic deformation is a hundred or a thousand times less; examples include polycrystalline aluminum and iron. Therefore, in order to interpret plastic deformations due to shear as they occur in reality, another model should be chosen.

2



PLANE DISLOCATION—The study of plastic deformations in monocrystals of particular substances has thrown a clarifying light on the process of plastic deformation.

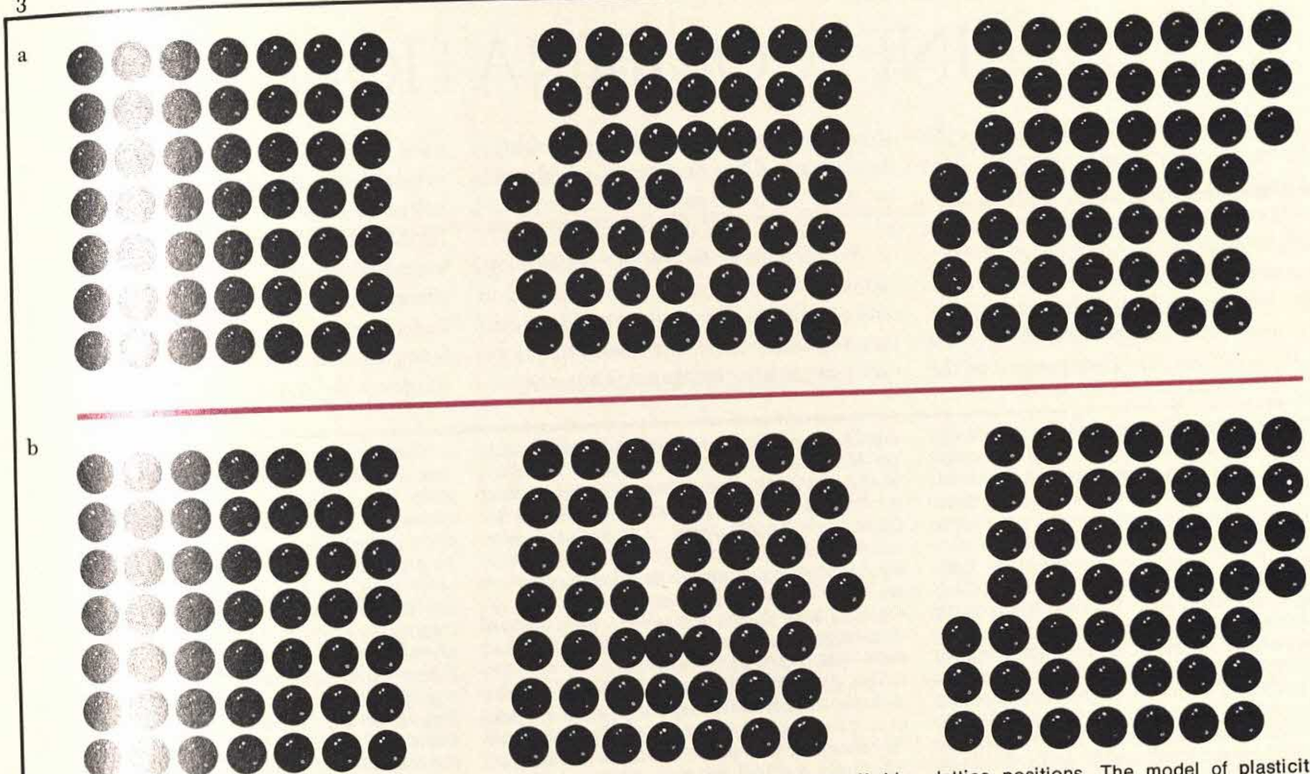
Illustration 2a shows how a cylindrical test piece of monocrystalline zinc deforms when it is subjected to tension. The lattice planes make an angle of 45° with the axis of the test piece cylinder. When the deformation has occurred (and this can be very extensive without producing a rupture), observation reveals that the test piece has deformed as if it were composed of playing cards, with the cards having slipped, due to tension, in respect to each other. This proves that the deformations occur because of the displacement of the lattice layers with respect to one another. It also proves that the mechanism of the displacement of the atoms must certainly be different from the one shown in Illustration 1.

Illustration 2b shows the model of a type of deformation that might be called a plane dislocation; it can explain the phenomenon of plastic deformation in crystals. Represented here are the atoms on both sides of the slip plane, but only on the end sections of the model. The atoms in the part above the slip plane are arranged at a slightly different spacing from that among the atoms in the lower part. Consequently, a progressive change occurs in the relative positions of the atoms of the two layers; that is, the atoms tend to be more and more out of phase along the row. The atoms are in phase at the extreme right and extreme left of the model, but they are out of phase at all intermediate points. In the right-hand half of the slip plane, the relative displacement of the atoms is always less than half of the lattice module; on the left-hand side, however, it becomes more than half this module. The line **AB,** which corresponds to a relative displacement of half a lattice module, is called the dislocation line. The direction of the dislocation, on the other hand, is perpendicular to this line and is indicated by the arrow **DD'.**

The structure of a dislocation of the type shown in Illustration 2b can be examined in somewhat greater detail with the help of Illustration 2c. It shows the arrangement of the atoms above and below the slip plane in the same section as in Illustration 2b, but the layout is now more complete. Rather than considering the atoms in the two parts as displaced with respect to each other, the upper part can be imagined as containing an additional layer of atoms stretched along the dislocation line. The atoms in the immediate area of the additional layer in the upper part are spaced slightly closer together than usual; in the lower part, in the immediate neighborhood of the "missing" layer, they are spaced slightly farther apart. This region with its exceptional characteristics, however, is of limited dimensions and affects only a small part of the lattice structure, a few layers at most.

A model of a dislocation may be obtained by means of identical soap bubbles floating on top of a liquid surface. The bubbles tend to form a lattice structure, but the pattern often is slightly imperfect, thereby forming models of dislocations. Illustration 2d shows such a soap bubble model. The defect can be observed when the illustration is viewed obliquely, from one corner to an opposite corner.

3

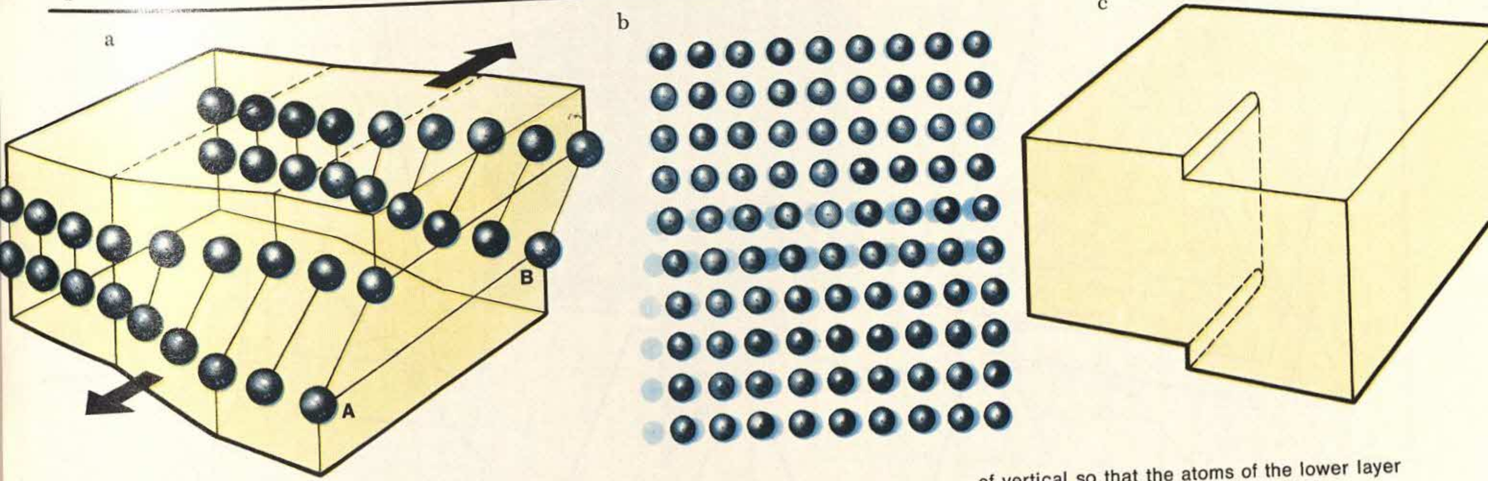


POSITIVE AND NEGATIVE DISLOCATIONS—The dislocations noted in Illustration 2c can be classified as positive and negative. A dislocation is positive when the extra lattice layer at the dislocation line is above the slip plane; it is negative when this extra layer is below it.

Illustration 3 shows that the plastic deformation corresponding to a shear stress can be readily interpreted by means of the dislocation model. The three illustrations in 3a are a case in point. At the left is a perfect crystal. If this is subjected to a shear stress, as the middle illustration shows, a positive dislocation will be formed; the center of the dislocation will move from left to right.

The three illustrations in 3b, on the other hand, show a negative dislocation that moves from right to left. This model shows that the deformation affects only a few rows of atoms at a time, displacing them from their correct lattice positions. The model of plasticity obtained through dislocation, therefore, provides an explanation as to why the force needed for plastic deformation is small compared to the force needed for an elastic deformation. The fact is that under stress not all the atoms above and below the slip plane become displaced at the same time; only those in the immediate vicinity of the dislocation do.

4



SCREW-TYPE DISLOCATIONS—A second type of dislocation, illustrated here, is called a screw-type dislocation because in the vicinity of the dislocation the atoms or molecules of the lattice are arranged like the steps of a spiral staircase.

Illustration 4a shows how the lattice layers are arranged at a screw-type dislocation. The lattice layers on the left are in a perfectly regular position; on the right, however, they have slipped by one lattice module. **AB** is the dislocation line. The screw-type dislocation, unlike the plane dislocation, involved the movement of the lattice layers in a perpendicular direction.

Illustration 4b shows how the arrangement of the atoms in a screw-type dislocation appears in a plane. In the upper part of the model, the atoms are perfectly superimposed on those of the underlying layer. However, in the lower part of the model, where the atoms are dislocated, they are displaced by an entire lattice layer. For the sake of clarity, the atoms in the upper part, where they are really in perfect superimposition, are shown as if they were slightly displaced. This part of the model, therefore, is drawn as if the viewer were looking at it from a direction slightly out of vertical so that the atoms of the lower layer can be better seen.

If the plane of the dislocation is arranged in a vertical direction, a parallelepiped consisting of a few crystalline bases presents itself (Illustration 4c). It looks as if a cut had been made in the side of a perfect parallelepiped and the two parts of the cut had then been displaced with respect to each other.

In the screw-type dislocation, just as in the case of the plane dislocation, the phenomenon affects only a few atoms in the immediate vicinity of the dislocation line.

CRYSTALLINE COMBINATIONS

Originally, the study of crystals was the study of minerals found in nature. This resulted in a thorough knowledge of natural crystalline forms and the way in which they develop. Knowledge of crystals was at first limited to classification. Later, however, scientists began to study the microscopic properties of crystals and, in particular, the arrangement of the atoms inside crystals. Thus mineralogy, the science of the description of minerals (naturally occurring chemical species) gave way to crystallography, the study of the structure of crystals. Crystallography is not limited to crystals found in nature; it deals also with substances synthesized in the laboratory, which may be either organic or inorganic. Thus, the science not only deals with natural quartz crystals, for example; it also deals with copper sulfate (synthesized in the sulfuric acid industry), vitamin crystals, and even the complex crystalline structure of proteins. Also of interest are the properties of crystalline substances that result from the atoms not being regularly arranged. The crystalline state is the or-

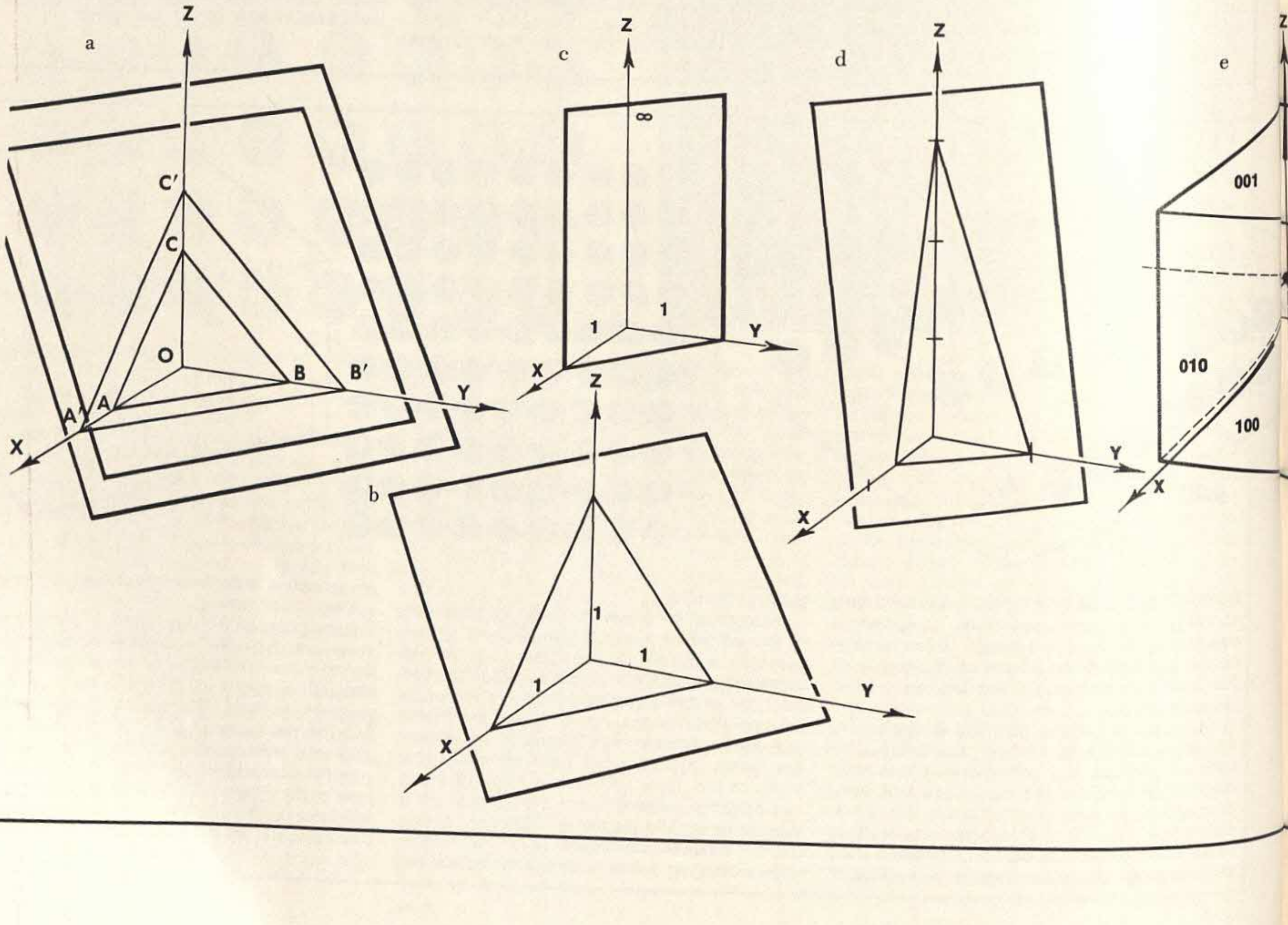
1

MILLER INDICES—A crystal is a solid body bounded by planes arranged regularly rather than irregularly in space. It is helpful to express the arrangement of these planes in terms of numbers. This requires the use of analytic solid geometry. Three straight lines, **OX, OY,** and **OZ** are drawn at right angles to each other, starting from a common point **O** and ending in arrows to show the orientation of the lines (Illustration 1a). Now a plane intersecting the three lines is drawn. If **O** is the origin of the lines, the plane will cut across them at three points, **A, B,** and **C.** Thus, the plane cuts the three lines into segments whose length is the distance between the origin **O** and the points of intersection **OA, OB,** and **OC.** These three line segments have different lengths that depend on the orientation of the plane in space. Now another plane is drawn parallel to the first plane and intersecting the three axes **X, Y,** and **Z.** The three new intersections are **A′, B′,** and **C′.** This defines three new segments: **OA′, OB′,** and **OC′** on the three axes. By simple geometry, **OA/OA′ = OB/OB′ = OC/OC′.** In other words, if coordinate axes are intersected with planes parallel to each other, segments proportional to each other on the axes are also intersected. Thus, for all these parallel planes the relation between the three segments of any one plane remains constant—**OA/OB/OC,** for example.

The property that parallel planes cut out mutually proportional segments on the three axes may be used to determine their position. For example, the plane shown in Illustration 1b intersects three equal-length segments on the **X, Y,** and **Z** axes. If the second plane is constructed parallel to the first and at a given distance from the origin, this distance will be equal for all three directions of the axes.

The plane in Illustration 1c intersects the **X** and **Y** axes but is parallel to the **Z** axis and does not intersect it. The plane may be regarded as intersecting the **Z** axis at ∞ (infinity), however. It can therefore be described as a plane intercepting the segments 1, 1, and ∞ on the three axes **X, Y,** and **Z.** These values are called the Weiss indices of the plane. On frequent occasions it is necessary to describe planes parallel to one or two axes. To symbolize the position of a crystal face, crystallographers usually take the inverse of the lengths of the intercepted segments and put them in parentheses. Thus, in Illustration 1b the indices of the plane are (111) and in Illustration 1c they are (110). This is because the inverse of 1 is 1, while the inverse of ∞ is 0.

The plane in Illustration 1d intercepts three segments of different lengths on the three coordinate axes at ½, 1, and 3. The indices of



dered state of matter; and as such, it is important in many fields of science.

This article deals with two important subjects: the method of representing crystal faces in terms of their orientation in space, and the way in which crystals associate when they grow in groups during formation. The simultaneous growth of several crystals does not always lead to an irregular arrangement. Crystals often develop at the same time and form quite regular aggregates.

GEOMETRY OF CRYSTALS

Miller indices are a useful way of describing crystal faces and their arrangement in space. Before discussing Miller indices, however, something must be said about the various ways in which adjacent crystals grow. To begin, the museum piece—the monocrystal—is an exception, a rarity usually found in rocks where it has been able to develop under special circumstances. The illustrations below describe some of the more common crystalline aggregates.

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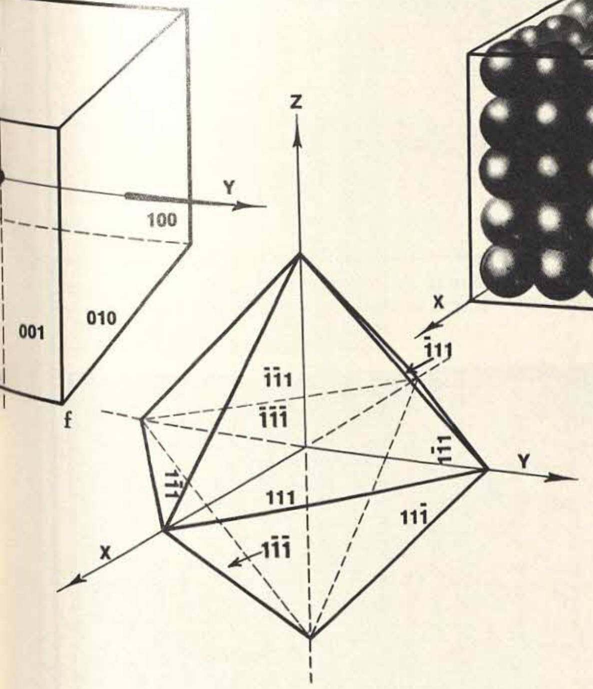
these three segments (their inverses) are thus 2, 1, and 1/3. To make things simpler, three proportional whole numbers (631) are used as the indices rather than a set that includes fractions. These numbers are obtained by multiplying all of the numbers by the factor needed to make the fraction a whole number. These numbers are called the Miller indices of the plane. If the plane intercepts an axis at a negative point, the resulting Miller index is also negative, as for example, **T** in the 100 plane (see below). The Miller indices can also be used with three coordinate axes that are not mutually perpendicular. Miller indices are widely used in crystallography because they give a rapid indication of the position of a plane of a crystal face or an internal plane. Some of their applications are illustrated as follows:

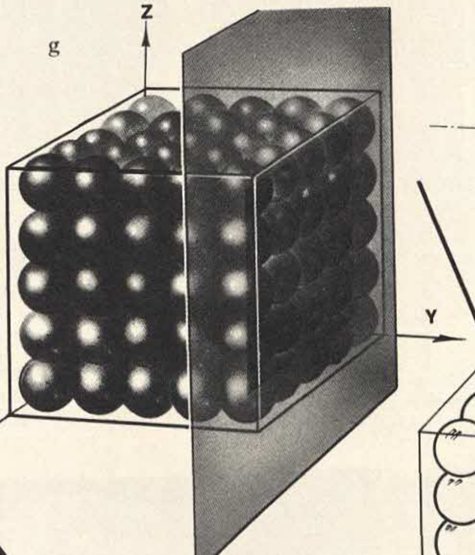
Illustration 1e shows the indices of the faces of a cube. This cube is oriented around the **X, Y,** and **Z** axes, with each of its faces intersecting one coordinate axis. In the case of the face intersecting the **X** axis, the indices are (100). The other faces show their indices.

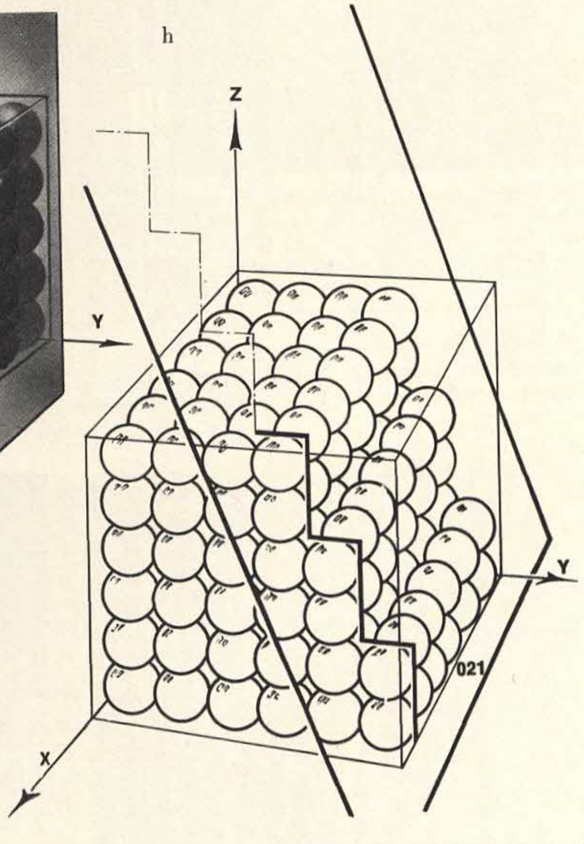
Illustration 1f shows the indices of the faces of a bipyramid. The bipyramid is oriented on the coordinate axes, with the indices of its faces shown. This is a special type of bipyramid; each face intersects the three coordinate axes at equal distances from the origin. The face completely included in the positive quadrant of the axes, for example, has the indices (111).

Miller indices can also be used to characterize the atomic planes within a crystal. The cube shown in Illustration 1g, for example, consists of atoms arranged in a cubic lattice. Each plane bounding the external surface of the cube contains all the atoms occupying that plane. This plane of atoms at the external surface (and all planes parallel to it) can be called an (010) plane, since it intersects only the Y axis.

Illustration 1h shows the same cube with some of the atomic spheres removed. The net effect is to form a series of steps pointing toward one of the faces. The steps are one atomic thickness long and two high. Thus, a cube with one of its faces steeply inclined is produced. The face intersects the axes at the points ∞, 1, and 2. Thus the Miller indices of the plane are 0, 2, 1, as the illustration shows. The same thing could be done with other planes formed by cutting different kinds of steps in the cube. Once again, Miller indices can be used to express the inclination and position of the plane. This application of Miller indices is very useful in the study of the atomic structure of crystals.







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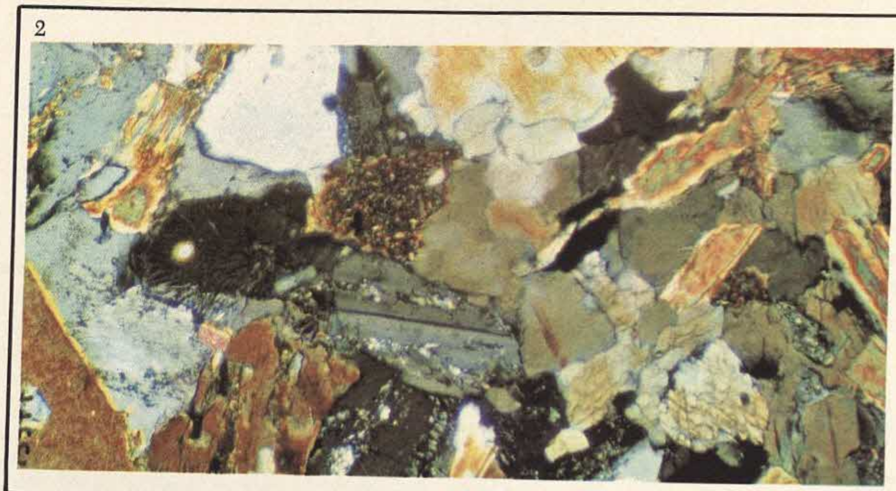
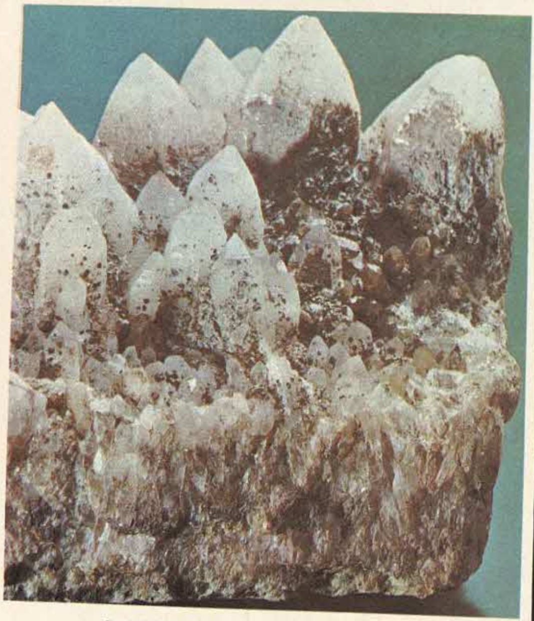


RANDOM ASSOCIATION—The photograph shows a sample of granite seen through a microscope under polarized light. Each part of the photograph having the same color is a single crystal that has grown in contact with others and is thus quite irregular in shape. Aggregates of this type show no regularity whatsoever.

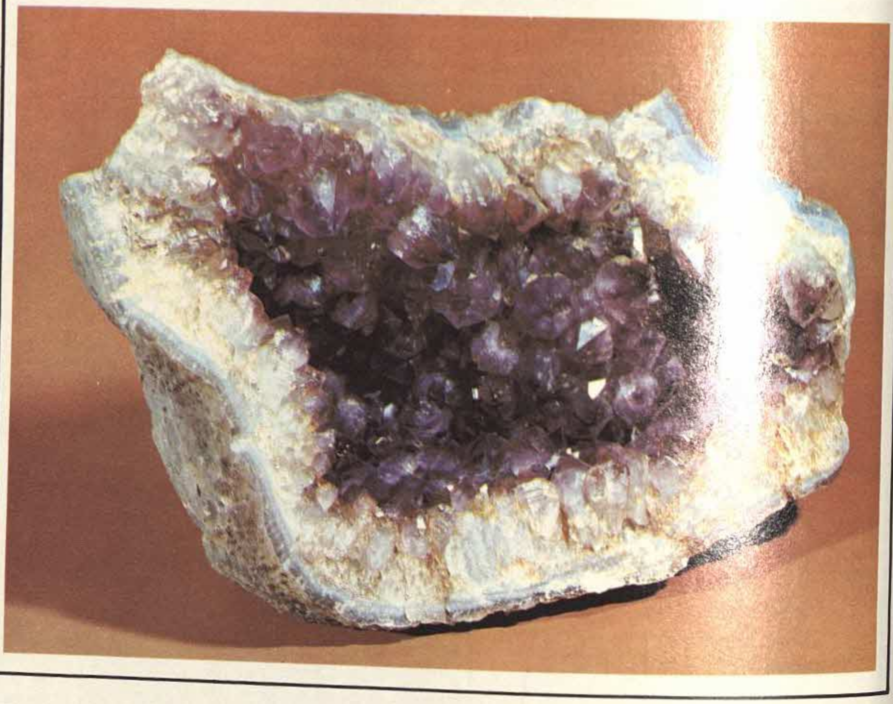
3



DRUSES—A druse is an aggregate of crystals grown from a single matrix having different sizes, lengths, and directions. All of the crystals display their characteristic growth patterns. This type of aggregate is irregular.

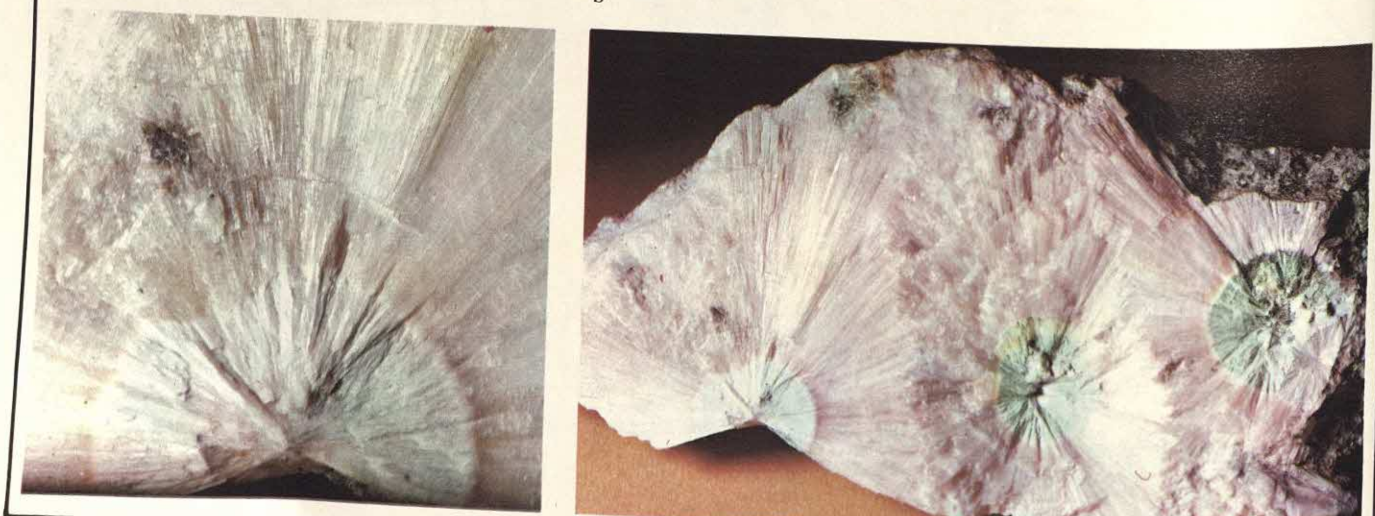
GEODES—A geode is an aggregate of crystals grown inside a cavity that originates from solutions or vapors. If a small section from the internal surface of a geode is taken, the crystals appear to be almost parallel—at least more parallel than those of a druse.

4

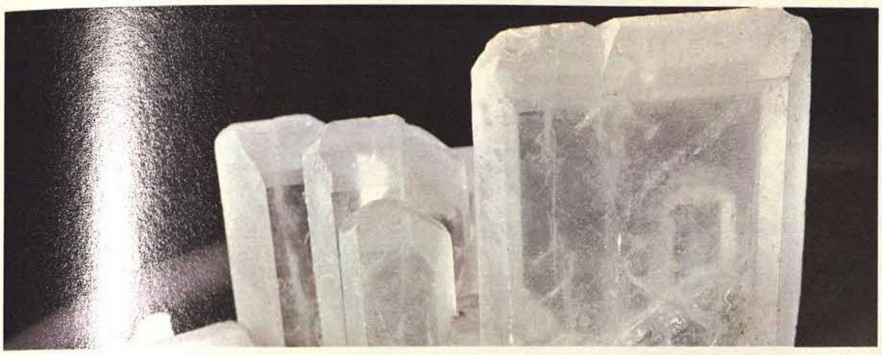


5

FIBROUS OR RADIATED AGGREGATES—Crystals sometimes grow with a certain degree of regularity, similar to the regularity of druse crystals. This occurs in the case of fibrous or radiated structures such as those shown in Illustrations 5a and 5b.



6



PARALLEL GROWTH — These crystals have grown somewhat like those in a druse, but they are more parallel.

7

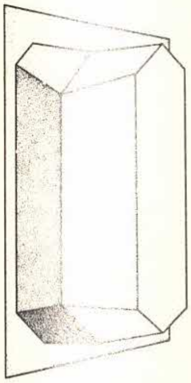
TWINS—In some aggregates of the same substance, the crystals have grown with a reciprocal orientation; these are called twins. One crystalline particle, for example, may be the mirror image of the other. The plane separating the two crystals is called the twinning plane.

In Illustration 7a the two elements of a twin and the twinning plane are shown. Sometimes the crystalline particles are arranged in such a way that one of them is rotated through a certain angle around an axis, called the twinning axis (Illustration 7b). Sometimes twinning takes place between two crystalline elements that grow into each other.

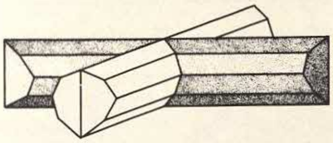
The diagrams and photographs show examples of twinning. Illustrations 7c and 7c′ show Japanese or knee twinning in rutile; Illustrations 7d and 7d′ show spinel twinning in cassiterite (a tin dioxide, SnO_2); Illustrations 7e and 7e′ show penetration twinning in fluorite; Illustrations 7f and 7f′ show iron cross twinning in pyrite; and Illustrations 7g and 7g′ show swallowtail twinning often found in calcium sulfate.

Many other forms of twinning exist. These have been studied by crystallographers and are used as a guide for the identification of minerals and rocks.

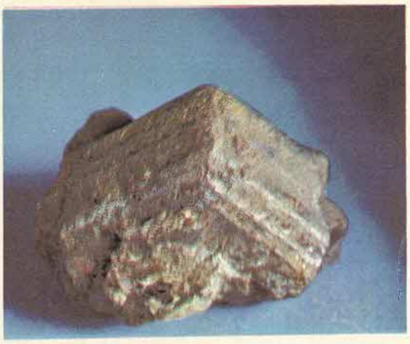
a



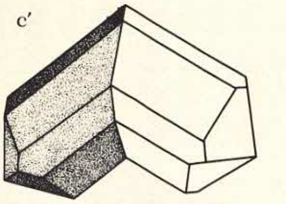
b



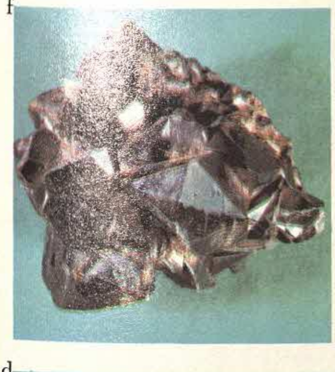
c



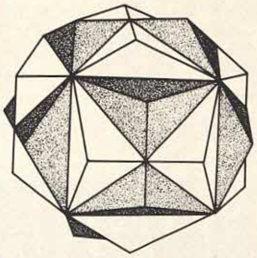
c′



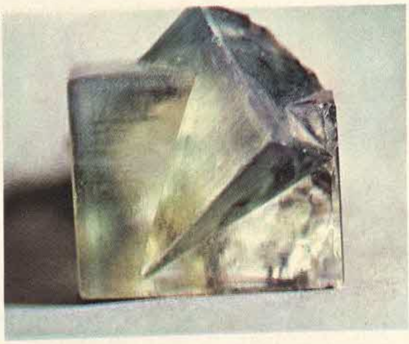
f



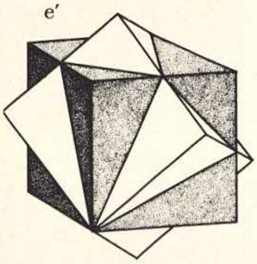
f′



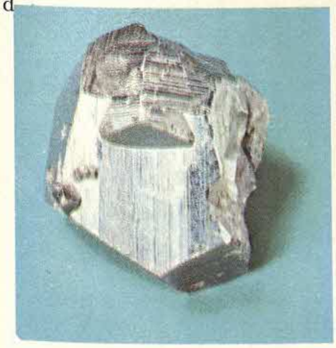
e



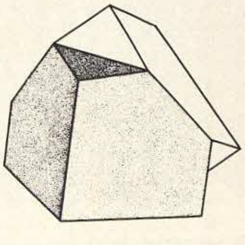
e′



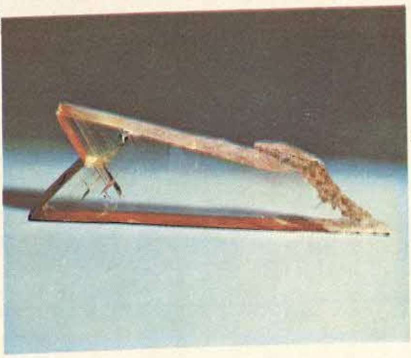
d



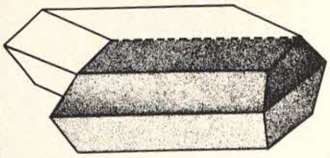
d′



g



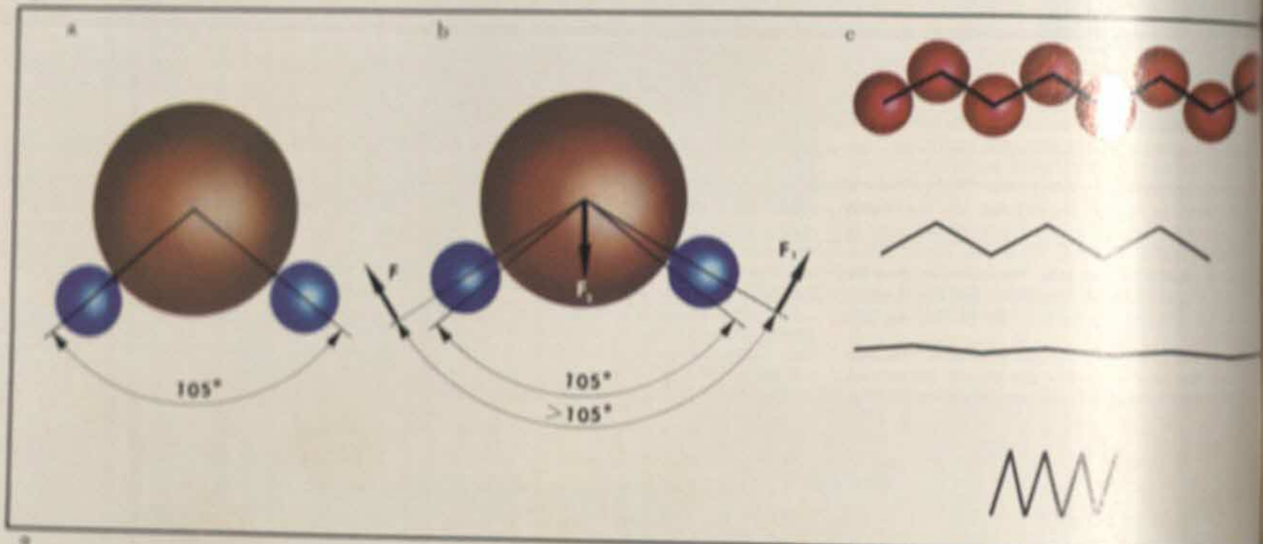
g′



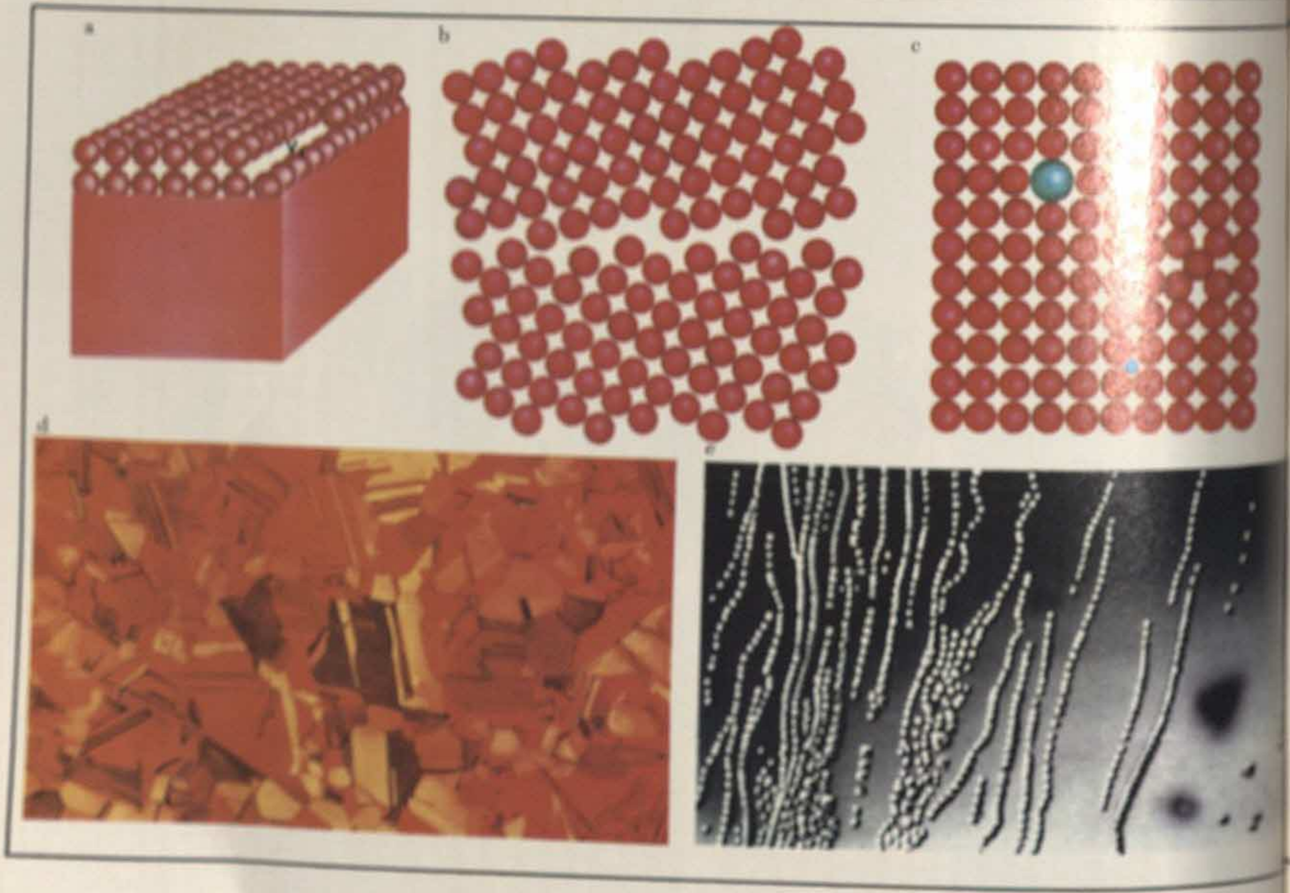
CRYSTALLINE DEFECTS AND THE PROPERTIES OF MATTER

mechanical properties
and internal structure

1



2



DIRECTIONAL BONDS AND THEIR ELASTICITY—To analyze the mechanical properties of real solids, the second characteristic of the atomic and crystallographic structure that must be considered is the elasticity and the direction of the chemical and crystallographic bonds. The water molecule represented in illustration 1a is formed by a large oxygen atom and two hydrogen atoms. The hydrogen atoms are arranged so that the centers of the three atoms define a circle sector of approximately 105°.

Illustration 1b shows what happens when an attempt is made to move the two hydrogen atoms so that their two centers and that of the oxygen atom will form a slightly greater angle than 105°. In this example, obviously a force must be exercised. However, it should be noted that when the effort is made to displace the two hydrogen atoms from their equilibrium position of 105°, a finite displacement by means of very small forces can be obtained, at least initially. This is so because the very definition of the production of an equilibrium implies that the displacement of these atoms, as long as it is infinitesimal, must be capable of being caused by very small forces.

What happens after the two hydrogen atoms have been displaced in such a way that they form a slightly greater angle than 105° with the oxygen atom? If this angle were increased still further, an effort would have to be exerted as represented by the three forces F_1, F_2, and F_3. This effort would have to be much greater than the one needed to produce an analogous displacement of the hydrogen atoms when they are aligned in such a way with the oxygen atom as to form an angle much closer to the initial 105°.

The structure of some molecules made up of many atoms is shown in illustration 1c. The atoms are not arranged in rectilinear rows, but rather in regular zigzag chains in which there is a succession of well-defined and constant angles. The succession of designs shows that this chain of atoms can be represented by means of a zigzag line (consisting of equal segments if the atoms in the chain are all small); this zigzag line represents the equilibrium position of the atoms. If the molecule is now made to suffer an impact, it will vibrate and the zigzag line can thus expand or contract as shown in the two lower lines of the illustration.

The characteristics described above have been concerned with a molecule, but these same characteristics can also occur in a crystalline structure; they are, therefore, very important for defining the structure and its attendant mechanical properties.

STRUCTURE AND CORROSION—A solid can be attacked or corroded by a chemical agent that has the possibility of reacting with it. The nature of this property of the solid obviously depends mainly on the chemical nature of the attacking agent and the attacked solid. Nevertheless, all things being equal, the imperfections present in the crystalline structure will exercise a considerable influence on the solid's vulnerability to chemical attack.

An atom missing from the upper surface of a cubic crystal causes a vacancy. The effect of this vacancy is that the atoms surrounding it find themselves in a state of imperfect equilibrium between the forces that hold them together. The outer shells of the electrons of these atoms are, therefore, subject to the attractions exercised by the attacking agent in a different manner from the way in which these attractions are felt by the other atoms in the crystal; usually this attraction is much stronger at the vacant point. This point constitutes a preferential place of attack by a chemical agent.

Once this attack has begun its work, the crystal will tend to lose a number of atoms and will be left with defects of the type illustrated at V, in illustration 2a, that is, steps representing particularly favorable places for the growth of the crystal. A defect that will favor the growth of the crystal also will favor chemical attack and, consequently, the destruction of the crystal.

The intersection of two perfect crystalline lattices is shown in illustration 2b. This intersection is another type of crystalline defect that favors chemical attack. Although there is no accumulation of interstitial atoms along the line of intersection, the very existence of the intersection between the two lattices involves imperfections constituting the points of attack. Even in a polycrystal with a very high degree of purity, the surfaces of the grains will constitute the preferential points for chemical attack.

In both illustrations 2a and 2b it can be seen that real solids, because of such phenomena as vacancies or a polycrystalline structure, are more vulnerable to chemical attack than ideal solids. A quenched steel, for example, where rapid cooling has "frozen" a large number of vacancies, is more vulnerable than the same steel after slow cooling or after quenching followed by annealing.

On the other hand, illustration 2c shows a crystalline solid containing interstitial or substitutional atoms. Both these types of defect constitute an irregularity of the electrical equilibrium of the crystalline lattice; this irregularity renders the lattice vulnerable to attack. Alloys, therefore, are generally less resistant to corrosion than pure metals; for example, a carbon steel is more readily corroded than pure iron. Another excellent example is provided by aluminum. Pure aluminum is highly resistant to corrosion, but even small amounts of impurities (5 to 10 parts per thousand) render it readily vulnerable to attack by many chemical agents, even when their concentration is very low; these agents include salt water.

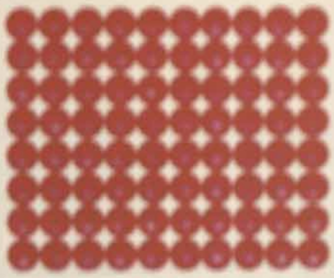
In like manner, the vulnerability of a polycrystal with impurities that have collected at the surfaces of the crystalline grains is much greater than that of a perfect monocrystal.

A metallographic specimen is shown in illustration 2d. The outlines of the various grains can be clearly distinguished. This specimen was obtained by polishing the surface of the metal and subsequently allowing it to be attacked by a corrosive agent. While this agent left the surfaces of the various crystals intact, it immediately attacked the border spaces between the crystals, because these were the places where all the impurities collected.

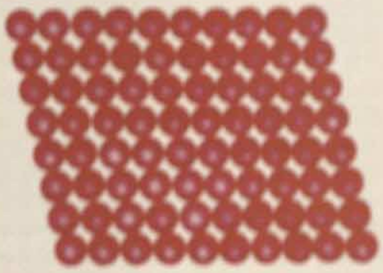
Of great interest is what happens in the case of metals with a high degree of purity and a polycrystalline structure, that is, metals that are relatively invulnerable to attack. When they are subjected to deformations (rolling or cold drawing, for example), they become filled with defects of the vacancy type and are thereby made more vulnerable to attack.

In illustration 2e the surface of a metal has been subjected to a cold working process that has produced defects in its crystalline structure. The chemical attack has taken place along the lines where the defects have accumulated in the form of pyramid-shaped indentations. The faces of these indentations are all oriented in the same direction as the crystallographic faces of the crystal itself.

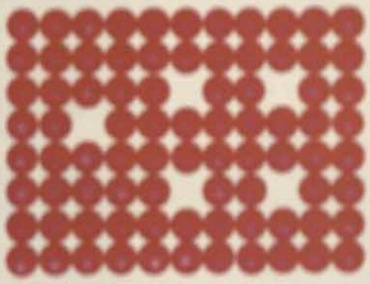
3a



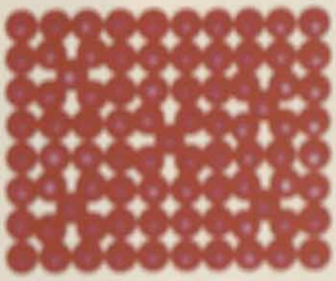
3b



3c



3d



THE ELASTIC PROPERTIES OF SOLIDS—The ideal arrangement of a cubic crystal structure is shown in illustration 3a. The same structure is shown in illustration 3b as it appears after having suffered a shear deformation. This deformation is best understood in the sense of compressing the atoms or dilating them, and in the sense of varying the angles of the bond between an atom and its neighbor. In this case the forces are similar to those described in illustration 1. These forces are not great in the case of pure crystals, but they can increase as soon as defects are introduced.

A crystalline structure analogous to the preceding ones is shown in illustration 3c; however, the structure has been profoundly altered by the presence of vacancies. The bonds in this structure are already more deformed than those in the structure shown in illustration 3b. Because it is more difficult to subject the bonds to further deformation, this type of crystal has a greater hardness than the structure shown in illustration 3b.

Another analogous structure is shown in illustration 3d, but this time it is full of interstitial atoms that produce the same effect as the vacancies and so lead to an analogous increase in the rigidity of the solid. This is attempted in tempering and in alloying.

No one begins the study of mathematics with calculus. A student first learns the essentials of basic algebra, geometry, and trigonometry before he is ready to cope with the intricacies of calculus. In like manner, if a person wishes to study real solids, he must first examine and become familiar with the basics of theoretical or ideal solids.

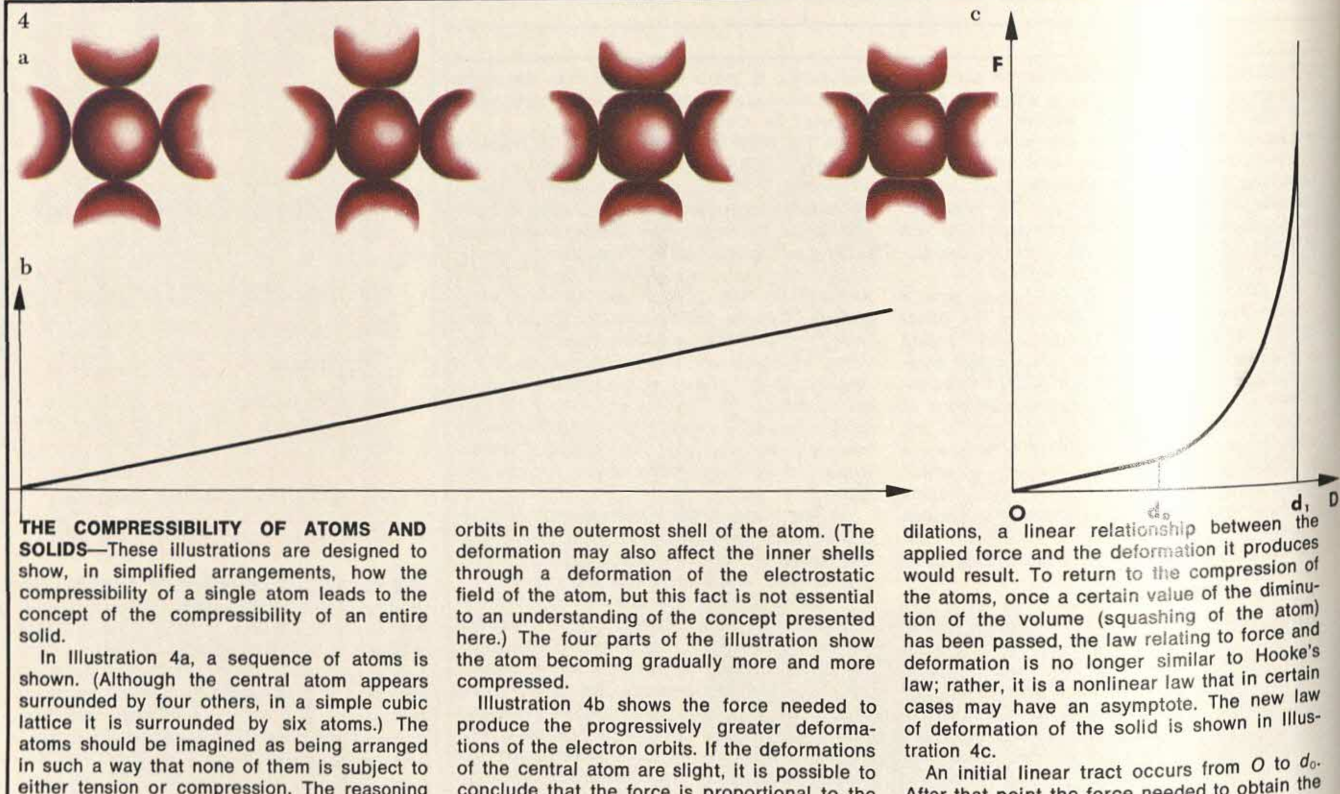
In the study of real solids, familiarity must first be established with some of their simpler characteristics, such as their crystallographic properties and the intensity of the forces that keep their atoms united or at the point of equilibrium. Once this knowledge has been achieved, it would then seem logical that most of the mechanical properties of these real solids could be calculated and predicted. However, this is true only in the case of particular types of solids.

Construction of the theory of ideal solids is extremely important because it constitutes the model for further theories that explain the structure and constitution of real solids. Although most solids are real solids, it is not possible to understand their properties unless the ideal solids have first been examined and understood.

A particular law must be understood before the theory of ideal solids and then that of the real solids can be constructed. This is the law of the compressibility of the atoms themselves. Lastly, the other characteristics of the atoms, such as the elasticity of the bond direction, must be learned. These characteristics form a foundation for the study of real solids.

Real solids are of great interest for two reasons: first, they are the solids used in all technological processes; second, and more important, is the fact that they can have certain properties that can be purposely constructed in the preparation of the solid itself. For example, the term *real solid* can mean some special steel with particular properties such as tensile or compressive strength, ductility or fragility, and so forth. The importance of knowing the theory of real solids, then, lies in the fact that it enables a scientist to decide how to treat a substance in order to confer on it certain desired properties.

Moreover, the properties of the real solids are once again determined to a far greater extent by the imperfections of their real crystalline state than by their ideal structure.



THE COMPRESSIBILITY OF ATOMS AND SOLIDS—These illustrations are designed to show, in simplified arrangements, how the compressibility of a single atom leads to the concept of the compressibility of an entire solid.

In Illustration 4a, a sequence of atoms is shown. (Although the central atom appears surrounded by four others, in a simple cubic lattice it is surrounded by six atoms.) The atoms should be imagined as being arranged in such a way that none of them is subject to either tension or compression. The reasoning applied to the arrangements shown in all these illustrations will lead to the same conclusions when it is applied to other crystalline structures (the simple cubic structure is used only for reasons of simplicity). The successive arrangements show the other atoms being squashed against the central atom as if the entire solid were being compressed. At the point of contact, the compressed atom and those surrounding it suffer a deformation; in practice, this is a deformation of the electron orbits in the outermost shell of the atom. (The deformation may also affect the inner shells through a deformation of the electrostatic field of the atom, but this fact is not essential to an understanding of the concept presented here.) The four parts of the illustration show the atom becoming gradually more and more compressed.

Illustration 4b shows the force needed to produce the progressively greater deformations of the electron orbits. If the deformations of the central atom are slight, it is possible to conclude that the force is proportional to the deformation itself. The applied force is plotted as the ordinate, while the deformation it produces is shown as the abscissa. In this case, therefore, it is possible for the force to be strictly proportional to the deformation, but only when these forces are small. The same reasoning can also be applied to the deformations that the central atom would suffer if, instead of a compression, a tension had been applied; the tension would have produced a dilation of the atom itself. Again, for small dilations, a linear relationship between the applied force and the deformation it produces would result. To return to the compression of the atoms, once a certain value of the diminution of the volume (squashing of the atom) has been passed, the law relating to force and deformation is no longer similar to Hooke's law; rather, it is a nonlinear law that in certain cases may have an asymptote. The new law of deformation of the solid is shown in Illustration 4c.

An initial linear tract occurs from O to d_0. After that point the force needed to obtain the compression increases far more rapidly; consequently, the curve rises almost vertically. The curve stops when it has arrived at the point d_1; more exactly, it stops there only in the graph, because from this point it may be assumed that the compression has such a profound effect on the atomic structure as to almost destroy it; what the curve does beyond this point is of no concern here, however, since the present study is confined to the physics of solids.

THE LAWS OF FLUIDS

the principles of hydrostatics

Hydrostatics is the branch of physics concerned with the properties of liquids at rest (that is, not in motion). Some of the principles of hydrostatics apply also to gases. Liquids and gases, in contrast to solids, are classified as fluids and have some common characteristics. Mastery of the principles of hydrostatics helps to provide the answers to many problems associated with everyday phenomena.

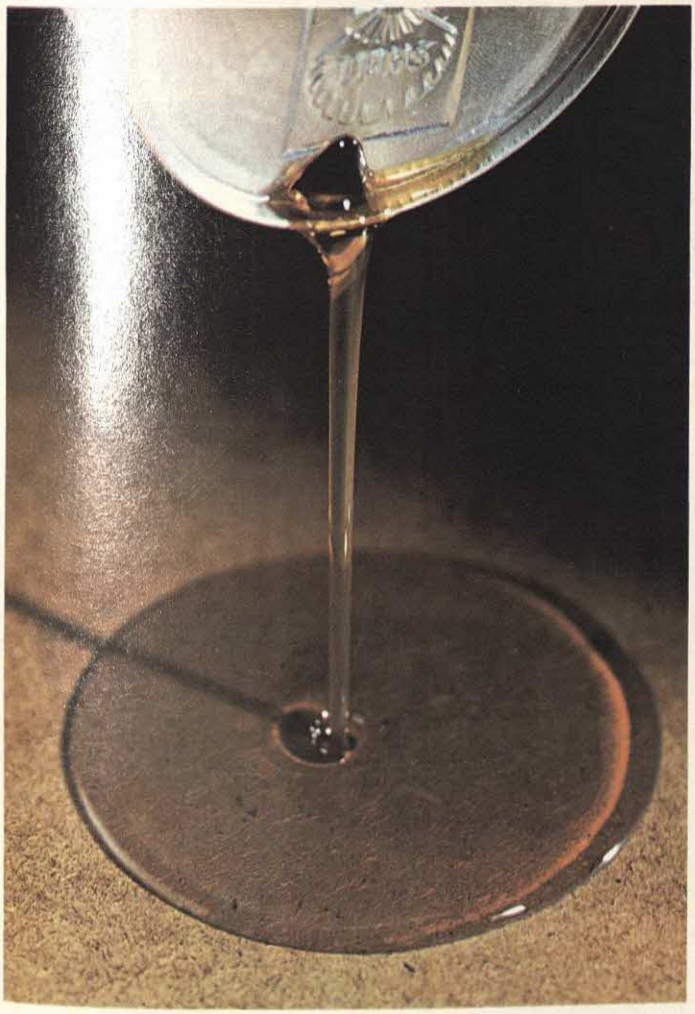
Why can water seeping under a dam cause it to collapse? Why does water gush out of an artesian well? Why does an inner tube of a tire lose air sometimes after having been mended with a patch? Why is a diver swimming in shallow water pushed toward the surface, whereas after reaching a depth of about 40 feet he finds it difficult to return to the surface? How can a comparatively small dike, such as those protecting the coast of the Netherlands, hold back the entire thrust of the ocean? How does the human body withstand the enormous weight of atmospheric pressure, amounting to as much as 15 tons?

Some of the answers to these problems are found in an understanding of the properties of fluidity and the behavior of fluids.

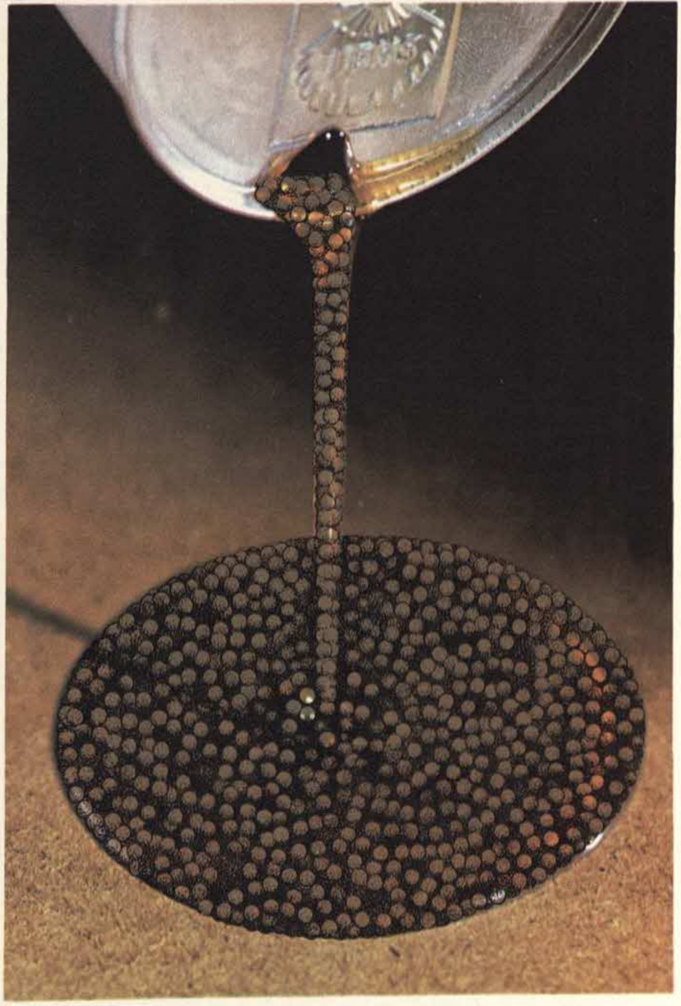
THE NATURE OF A FLUID—If oil is poured on a flat, horizontal surface, it does not stay still, but continues to spread (Illustration 1a). This is explained by the mobility of the molecules of a fluid, which apparently slide over each other with little friction. This property of a fluid enables it to adapt itself quite readily to the shape of an object that contains it or that is submerged in it, and to exert force on these objects in every direction. The molecules can be compared to minute spheres that are not bound by attraction to one another to such an extent that they tend to form a solid body. The molecules, like such spheres, spread when poured onto a horizontal surface (Illustration 1b).

In the other examples discussed here, the objects under discussion are liquids. Gases are also fluids; but unlike liquids, gases can expand as well as spread. A liquid poured out of a container always maintains its initial volume, but a gas poured out of a container expands into whatever volume is available, no matter how large. Conversely, liquids are virtually incompressible, but it is possible to reduce the volume of a gas by forcing it under pressure into a smaller container. The volume of a liquid can be reduced only under extremely high pressure.

1a



1b



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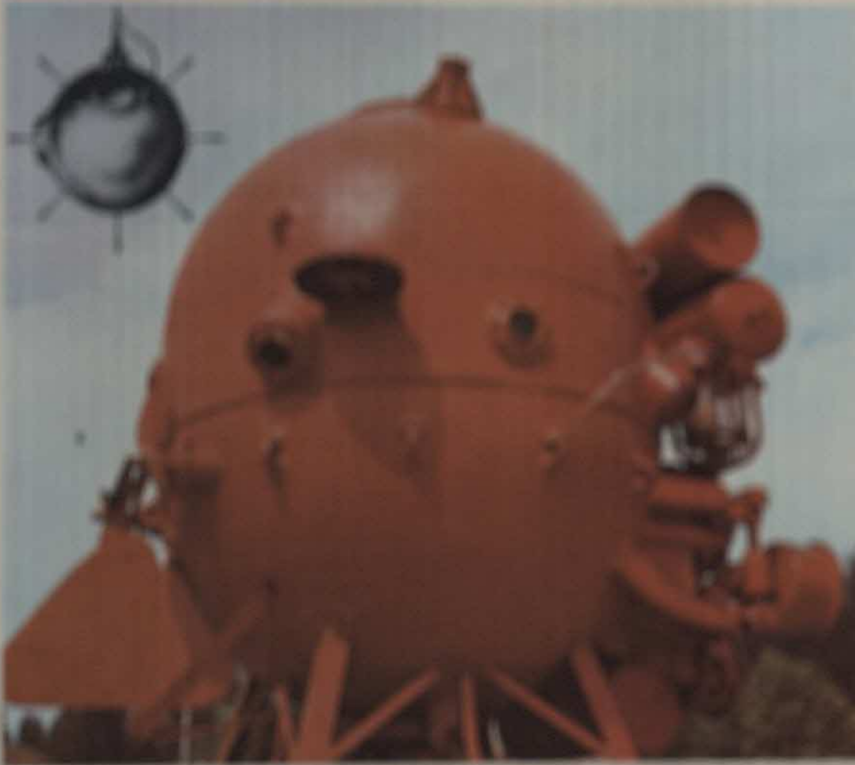

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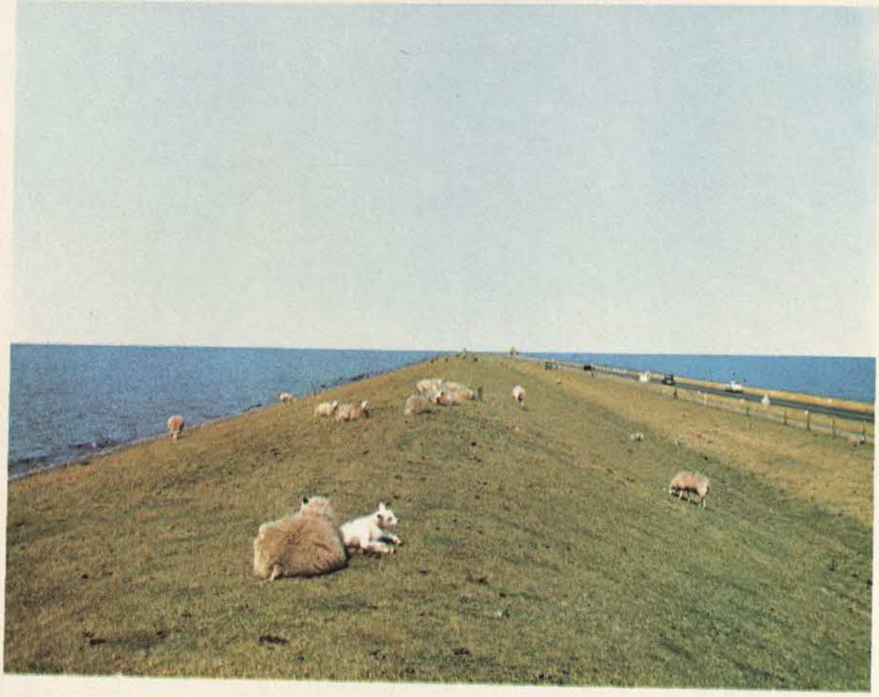
FLUID STATICS | a lever made with water

The huge dikes that keep the sea from flooding the Netherlands have always fascinated students of geography. For physicists, however, the attraction of the dikes is due to more than simple curiosity. These huge earthen bulwarks help form a king-size, seawater-filled receptacle that helps explain the fundamental principles of fluid statics, the branch of science that studies the equilibrium of liquids and gases.

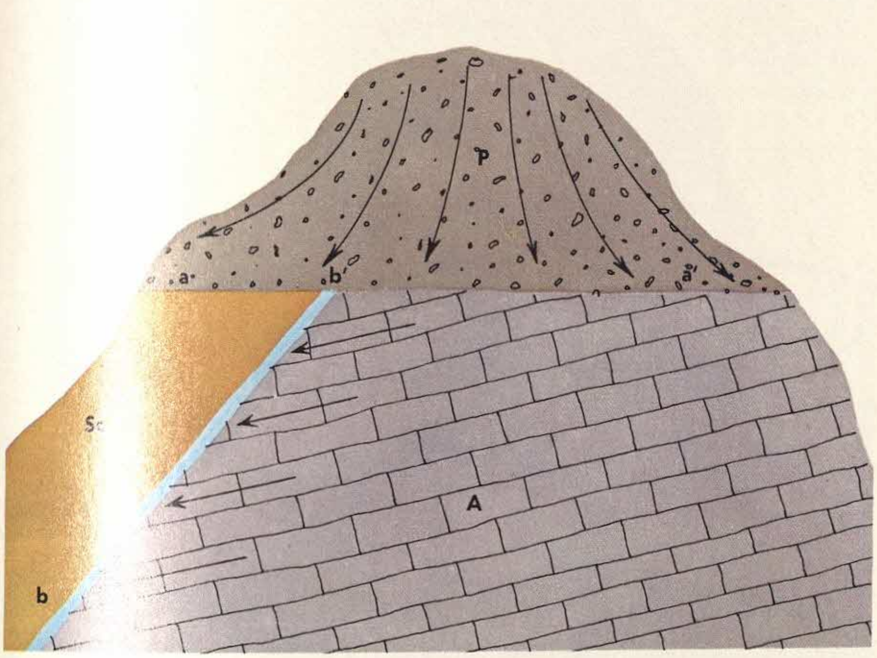
Because of its weight, any liquid enclosed in a receptacle of any shape or size exerts a pressure on the walls and bottom of the container and on any bodies that are immersed in it. Examples from daily experiences and an examination of some simple phenomena will answer several questions that come to mind in the course of even a cursory probe of fluid statics.



THE THICKNESS OF A DAM THAT HOLDS BACK THE ENTIRE SEA—The pressure a liquid exerts on a surface is independent of the orientation of that surface. For example, the water at the bottom of a receptacle will exert the same force on each square centimeter of the base and adjacent walls. On the other hand, the pressure varies with the depth (more precisely, it is directly proportional to the depth) because the pressure depends on the height of the column of water that weighs on each element of surface, and this column extends all the way up to the top. The pressure exerted by the water at the bottom of a sea or lake is very great: the weight bearing down on each square centimeter of the bottom of a basin 1,000 m (about 3,300 ft) deep is equal to 100,000 cm³ (about 6,100 in.³) of water, that is, 100,000 g or 100 kg (about 220 lbs). To construct a dike similar to the one illustrated, which is part of the dike that prevents the sea from flooding the Netherlands, an engineer would have to make certain that his wall of earth was thick enough to withstand the pressure exerted at the sea bottom. The thickness would depend only on the depth of the water at the base of the dike. A rather small earthen dike would be quite sufficient to hold back an entire ocean if the depth of the ocean were only 10 m (about 33 ft).

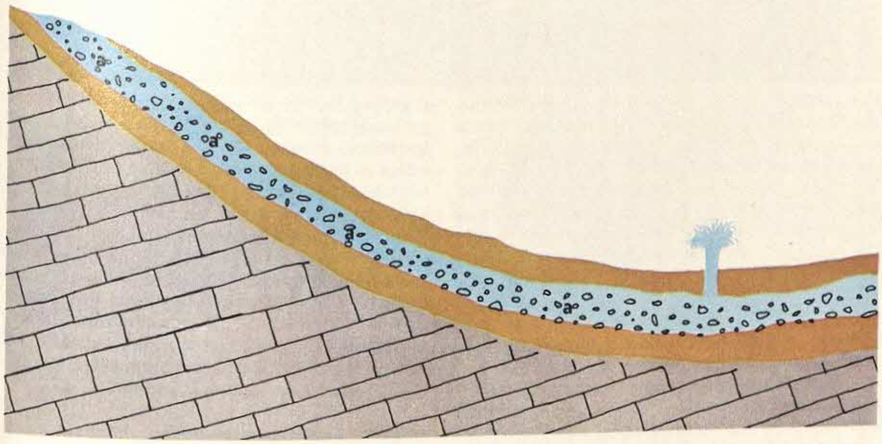
THE DAM OF A SMALL LAKE—This dam holds back the waters of a reservoir that has about the same depth as the basin shown in the preceding illustration. While the basin in the first illustration extended into the Earth's ocean system, here the extent of the water is small since the basin consists of a small, man-made mountain lake.

Nevertheless, both the dike in the first illustration and the dam shown here are subject to the same thrust (except for the fact that the mountain lake will not be subject to heavy seas or tidal waves); therefore, essentially both can be constructed with the same dimensions. Again, in practice, the force exerted on a dam depends solely on the depth of the water it holds back and not on the horizontal size of the lake that the dam creates.

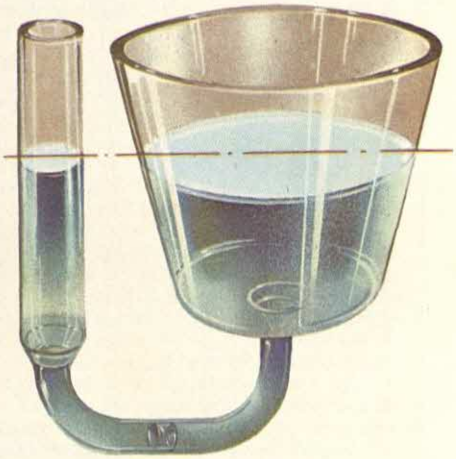


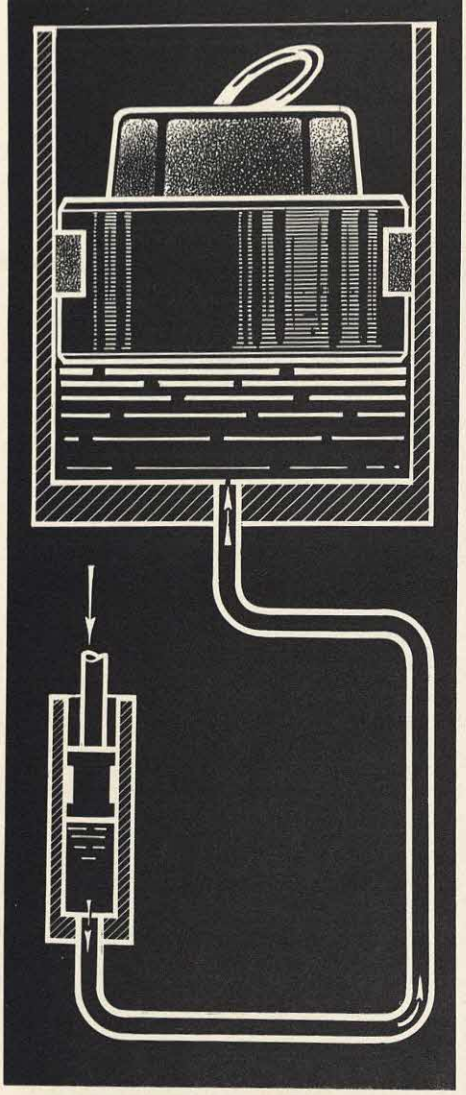
HOW A WATER SEEPAGE CAN CAUSE A LANDSLIDE—The amount of water found in the ground depends on the porosity of the soil or rocks: water will percolate very easily through porous materials (sands, gravels, rocks with fractures, or cavities such as those in karst-type limestones); it cannot cross impermeable layers of rock (compact rocks like granites and clays, for example). The water that collects in the upper parts of mountains (**P** in this illustration) finds permeable ground and percolates down as far as the line **aa′**, where it encounters a different type of rock. At this point some of the water comes to the surface in the form of springs. However, the remainder will percolate through the rocks **A**, which are permeable in the direction indicated by the arrows. This happens because the water does not succeed in penetrating into the rocks **Sc** (clays), for these are impermeable. The water percolating through the rocks **A** will therefore collect along the contact line **bb′** between the two types of rocks and build up a considerable pressure, due to the difference in level between **b** and **b′**. This pressure cannot be relieved by means of seepage through the clay, and it may, therefore, build up to such an extent that it pushes the whole clay mass outward, thereby causing a landslide.

ARTESIAN WELLS—In a large valley having walls covered with permeable soils, water percolates into the ground and sometimes succeeds in seeping downward into the permeable layers along the axis of the valley. The ground at the center of the valley may consist of alternate layers of permeable and impermeable material. Any water that infiltrates into the permeable material between two impermeable layers will be subject to the pressure exerted by the weight of the water in the upper parts **aaaa** of the permeable layer. If a well is now drilled in the valley from the surface down to the permeable layer, the water will gush out and will tend to rise to the same height as the highest part of the permeable layer, which is completely impregnated with water.



CONNECTED VESSELS — The liquid flows from one vessel into the other until it attains the same level in both; the pressures exerted on the two sides of a membrane placed in the central part of the connecting tube are equal. These pressures, according to Stevin's principle, depend only on the difference in level between the point at which the membrane is placed and the two free liquid surfaces.





THE "HYDRAULIC LEVER"—The illustration shows two connected cylinders; one has a large diameter and the other a small one. Both cylinders are full of the same liquid and their open ends are closed by pistons that are free to move up or down. What happens if the larger piston is kept in a fixed position while pressure is exerted on the liquid with the small piston? This pressure will affect the whole mass of the liquid and not just the liquid in the areas closest to the small piston. This phenomenon is known as Pascal's principle, taking its name from the French physicist-mathematician who first deduced it from the laws of mechanics. Thus, if the small piston has an area of 1 cm^2 (about 0.15 $in.^2$) and a force of 1 kg (about 2.2 lbs) is exerted on it, all of the liquid in both cylinders will be subjected to a pressure of 1 kg/cm^2 (about 14 $lb/in.^2$). In the large cylinder this pressure will now be applied on a much larger area—100 cm^2 (about 15.5 $in.^2$), for example—and will, therefore, exert a force of as much as 100 kg (about 220 lbs). By applying the modest force of 1 kg, a much greater force is developed: a force of 100 kg in this particular case.

However, the work performed by the two pistons must be the same; therefore, the small piston will have to be moved through a distance of 1 m if the large piston is to be lifted by 1 cm (about 0.4 in.). The situation is analogous to that of a lever. Considerable forces can be exerted by means of levers, but these forces can act over only a very short distance, and the long arm of the lever will have to be made to travel over a much greater distance. The principle illustrated here lies at the basis of the hydraulic jack and the hydraulic press.

BALLOONS—From the end of the eighteenth century and throughout the nineteenth, man's only hope of flying lay in the possibility of rising from the ground with the help of a balloon, a sphere made of thin, impermeable cloth filled with a gas (hot air, hydrogen, or helium) that was lighter than air. The airplane has made the balloon obsolete as a practical means of flying; nevertheless, balloons still help provide the detailed weather information that pilots must have to fly an airplane safely over long distances. This information is obtained every day by small, hydrogen-filled weather balloons equipped with appropriate instruments and a radio that transmits meteorological data to a ground station. Balloons are also widely used to study such things as cosmic radiation and terrestrial magnetism. The principle that enables a balloon to fly is based on Archimedes' principle: balloons are lighter than air, and the upthrust that air exerts on all bodies (but that is usually insufficient to make them float because they are heavier than air) therefore causes balloons to rise. At sea level, the average weight of a balloon filled with hydrogen is about 100 g/m^3 (about 0.004 lbs/ft^3). Since air weighs about 1.3 kg/m^3 (about 6.2 lb/ft^3), the balloon will be subject to a net upthrust of about 1 kg/m^3 (about 0.06 lb/ft^3).

THE MOTION OF FLUIDS | explanatory experiments

Many characteristics of the mechanics of solids are difficult to understand and are far from obvious. In the study of the mechanics of fluids—hydrodynamics, the science of the motion of fluid bodies—common sense alone will usually lead to confusion. However, experiments in hydrodynamics are not especially difficult, require only limited equipment, and sometimes are rather dramatic.

For example, it seems natural to think that a body at rest, when struck by a body in motion, will itself be set in motion and move in the direction followed by the body that struck it. However, when the body in motion is a fluid, the body struck by the fluid may begin to move against the flow of the fluid.

An exact interpretation of these phenomena will provide considerable insight into the entire subject of hydrodynamics.

1

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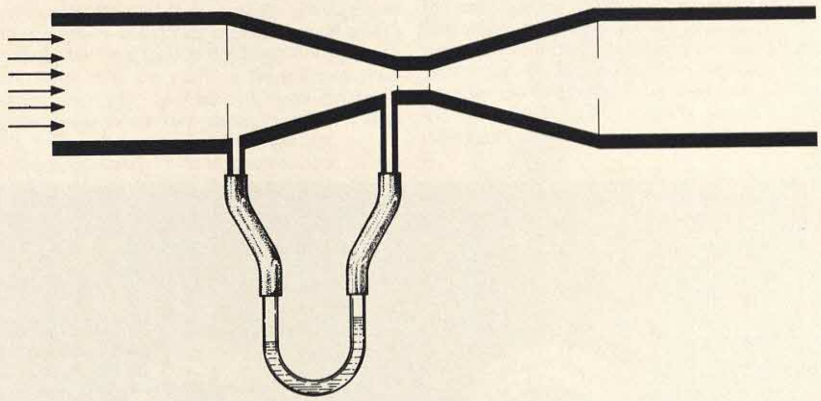

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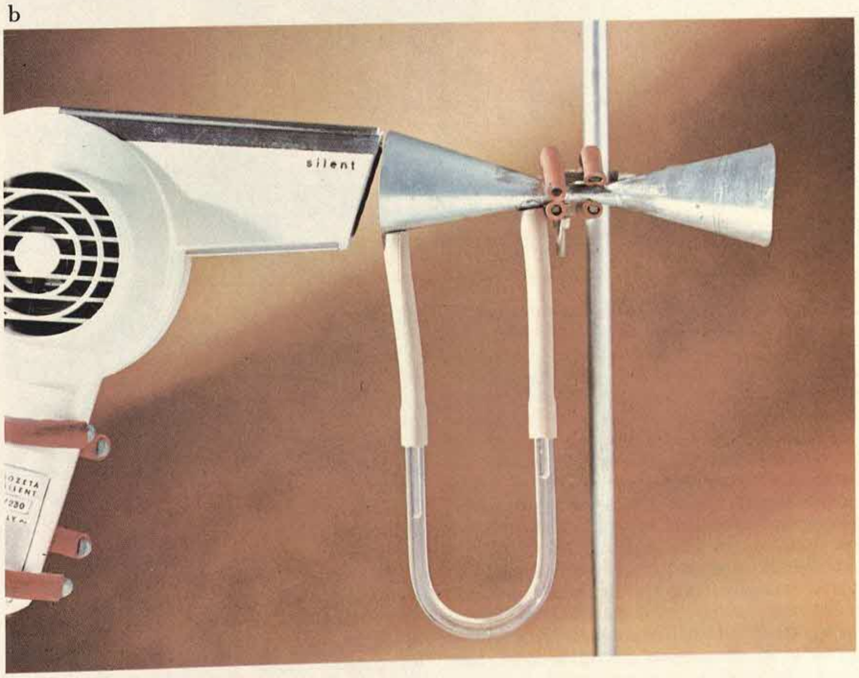

THE VENTURI TUBE—This simple device is an application, in a sense, of Bernoulli's principle. If the effect of the potential energy on a fluid from its head (the vertical distance between the surface of the fluid and the point of flow) is ignored—as can be done in the case of a horizontally flowing liquid—Bernoulli's principle concerns the relationship between the pressure and the velocity of the liquid, a relationship that is inverse. If the fluid is moving in a pipe with diameters of varying size, the velocity and the pressure will also vary; the pressure determines the motion through the pipe (if there were no pressure, there would be no motion); if the fluid gains velocity, through a constriction in the pipe, for example, the pressure decreases. In a pipe with varying diameter, therefore, the pressure will be lowest where the diameter is smallest. This principle is applied in the Venturi tube.

Illustration 1a is a cross section of a Venturi tube, showing the wide parts of the tube constricted by a smaller part where they join, with holes at the bottom of the tube—one at the wide part and one at the narrow part—fitted with secondary tubes linked to a liquid-filled U-tube. Air is blown through the main tube from the left, as indicated by arrows, and as it passes from the area of the first outlet to the second, the passage is constricted and the air pressure decreases. The greater pressure of the air at the first outlet will force the level of the liquid in the U-tube connected with this outlet to a level below that of the end of the U-tube connected with the second outlet, where the air pressure is less. If the U-tube is calibrated, the numerical value of the difference can be used to determine the velocity of the air passing through the main tube.

A Venturi tube can be constructed by using the materials shown in Illustration 1b. Two truncated cones can be made from cardboard or several sheets of paper joined with vinyl glue, or else sheet metal or "tin" from a tin can may be used if properly shaped and soldered. Two small tubes, about 4 mm (about 0.15 in.) in diameter, are joined to the outlets at the wider and narrower base of one of the cones, and these must be connected by flexible sections of rubber hose with a U-tube of any diameter, even as little as 2 mm (about 0.08 in.) and preferably not more than 5 mm (about 0.2 in.) where the hose is attached. This hose-and-U-tube arrangement, in effect a manometer, must contain some liquid, preferably colored water, so that changes in level in the U-tube may be observed and, if desired, calibrated. Now, air may be blown into the Venturi tube with a hair drier—a very useful source of a steady flow of air for many aerodynamic experiments. It is also possible to connect the air source with the Venturi tube by a flexible hose, with a method of varying the aperture at the point of connection in order to vary the quantity and, therefore, the velocity of the air entering the tube. This would make it possible to construct a graph indicating differences in pressure, as shown on the calibration of the manometer, as a function of the velocity of the airstream.

2

THE PITOT TUBE—This device, invented by a French physicist, Henri Pitot, is essentially a tube with a short arm bent at a right angle to a long arm, inserted into a fluid (liquid or gas) so that the stream flows into the short arm causing a rise in the level of fluid in the long (perpendicular) arm; the rise in level increases in proportion to the velocity of flow. The principle of the Pitot tube shown in Illustration 2a is an adaptation of the principle of the Venturi tube, in which an increase in velocity of flow is reflected in diminution of pressure. The Pitot tube is partially inserted into a streamlined object in such a way that one end of the tube (at the upper opening) receives the flow of the stream at its normal velocity and the other end (at the lower opening), separated from the first by a U-tube, receives the flow at its diminished velocity, caused by the shape of the streamlined object. The difference in pressure resulting from the difference in velocities is indicated by the difference in levels within the U-tube. If this U-tube is properly calibrated, it can register different velocities and can be used to measure the speed of motorboats and other vessels; it can also be adapted to measure airspeed.

Illustration 2b shows the materials from which the version in Illustration 2a can be made. The streamlined object is made of gypsum, in which is set the glass tube, bent as shown, and if desired reinforced with a piece of metal to anchor it in the gypsum. The tubing is of glass strong enough to withstand the mechanical forces that will be exerted on it, and has an internal diameter of 3 mm (about 0.12 in.). The entire device remains completely still in the flowing water; the stream will enter the tubing and rise to a higher level in the section connected with the gypsum block.

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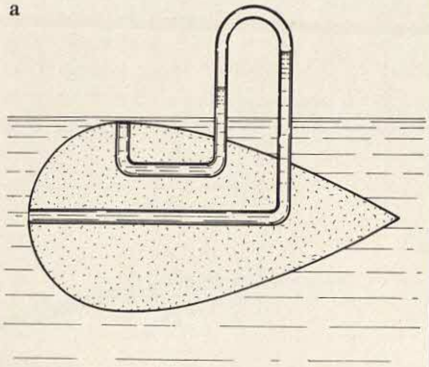

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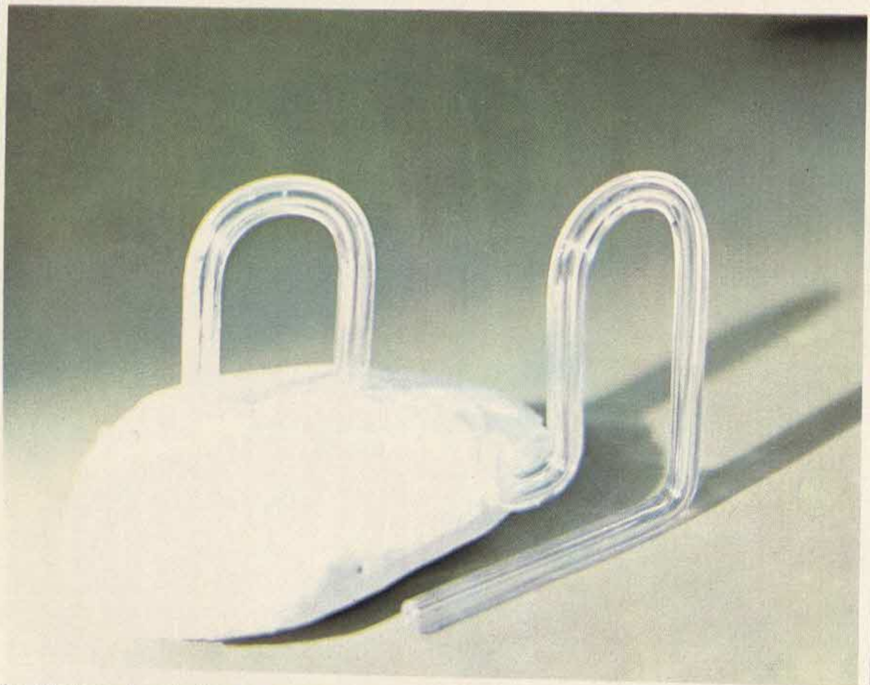

3

a

AERODYNAMIC PARADOXES — Bernoulli's principle, which is the basis for the functioning of the Venturi and Pitot tubes, also accounts for several phenomena that appear to be contrary to common sense, and are there-

4

THE CONSERVATION OF THE QUANTITY OF FLOW—This is another paradox derived from Bernoulli's principle.

Illustration 4a shows a funnel-shaped tube into which a fluid stream is moved as shown

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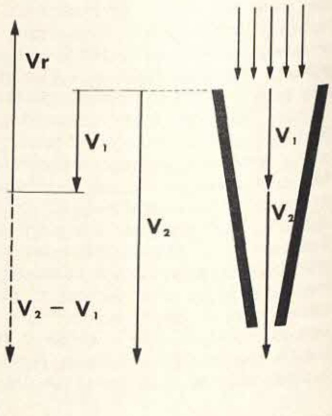


fore considered aerodynamic paradoxes.

If one blows between two sheets of paper, instead of separating, as might be expected, they cling together. If the two sheets are almost in contact with each other and stick together at the edges, like the pages of a new book, a slight breath of air will help separate them; but this will not happen if the two sheets are almost an inch apart. Illustration 3a shows the best way to make the experiment. The page is held with the left hand, as shown; the right hand keeps half of the open volume raised to an almost vertical position. The experimenter then blows between the pages. The open page will tend to close, and the more violently one blows, the more rapidly the page will close.

b

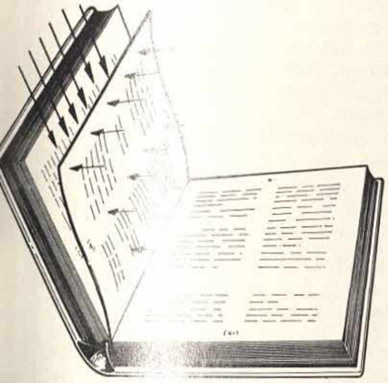
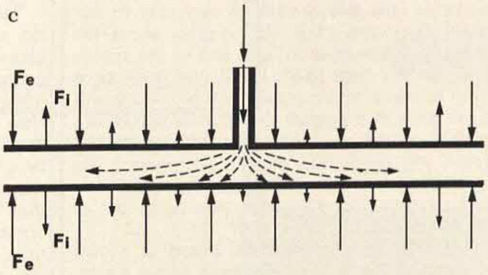


Illustration 3b explains the phenomenon shown in the photograph. When the breath leaves the mouth, the air is traveling very rapidly and its pressure is therefore very low; as it follows the path indicated by the arrows (on the left) it enters the confined space between the pages, drastically loses speed, and gains pressure until it is at about the equivalent of atmospheric pressure. At the same time the atmospheric pressure acts against the other side of the loose page (arrows at the right) and presses it against the rest of the book.

An even more striking paradox is shown in Illustrations 3c and 3d. A small hole is made in the center of a cardboard disk, and a glass tube, with an internal diameter of about 5 cm (about 2 in.), is inserted into the hole. A second cardboard disk is now held lightly against the underside of the first disk, and air is blown through the tube so that it passes between the two disks. Now the hand is taken away from the second disk; instead of dropping, it will remain suspended very close to the first disk and, with care, may even be lifted up.

The explanation is analogous to that in the preceding experiment: the air blown downward, at high speed and therefore low pressure, enters the restricted space between the disks; the pressure is lowest where the arrows are shortest, but as the air reaches the rims, it approaches atmospheric pressure; its downward force is represented by the arrows F_i, and this force is always less than the full atmospheric pressure outside the disks, represented by the arrows F_e. As a result, the lower disk will be pushed upward.

c



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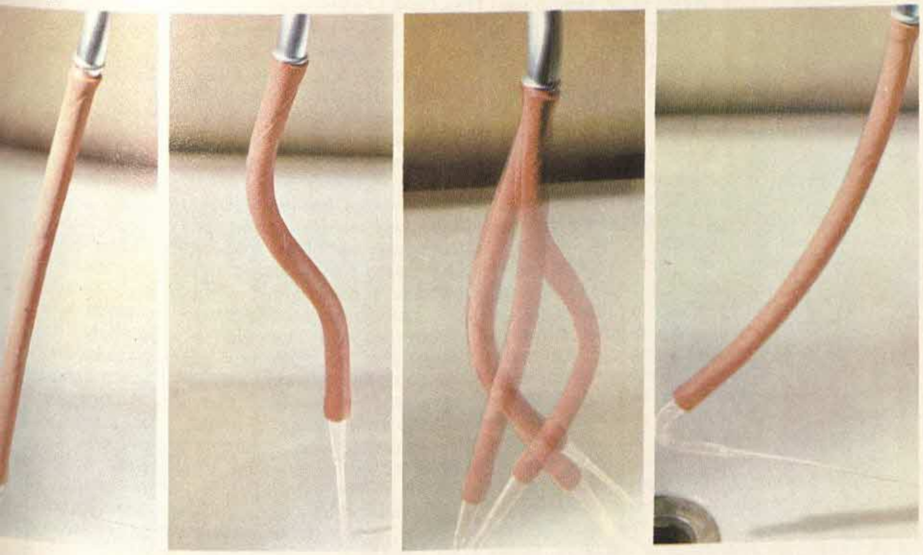

by the arrows. The tube might be expected to be pushed forward in the direction of the flow, but actually it is thrust backward. The illustration shows why this happens: the stream moves relatively slowly at the entrance to the funnel, as indicated by the length of the arrow V_1, and gathers speed as it reaches the narrow part of the funnel, as indicated by the longer arrow V_2. Inasmuch as the mass of the stream must pass all parts of the tube at an identical rate of speed, it acquires added velocity forward (in the direction of the arrows), while the funnel-shaped tube is subject to a reaction backward in the direction of the arrow V_r—against the direction of the stream.

In Illustration 4b, which depicts the phenomenon, a glass nozzle (which can be made by heating a glass tube over a flame and drawing it to shape) is attached to the end of a thin, flexible rubber hose that is, in turn, attached to a water faucet. The hose, left free to move, will recoil as soon as the water passes through the nozzle. If the water pressure is strong, the recoil becomes more pronounced as the nozzle opening is narrowed, increasing velocity.

VISCOSITY AND THE MOTION OF FLUIDS

laws and measurements

Viscosity, which may be defined as the internal friction of fluids, is a most important property, especially of fluids that are used as lubricants. Every lubricant, for example, must have a degree of viscosity suitable for the use to which it is to be put. Lubrication is crucial in a mechanized world. Inasmuch as the property of viscosity is related to the motion of fluids, whether while flowing on a surface or (if they are lubricants) between the surfaces they are intended to lubricate, it is necessary to inquire further into the motion of fluids.

1

THE VISCOSITY OF FLUIDS—No fluid, whether liquid or gas, has a form or shape of its own; all fluids assume the form or shape of the container in which they happen to be. This characteristic of fluids is due to the relatively small cohesive forces that hold together the molecules of fluids, allowing them freely to change their positions with respect to one another without necessarily changing their volume.

In formulating the principal theories and laws of fluid dynamics, it is customary to consider only ideal fluids. Just as the laws of thermodynamics that govern ideal gases can be applied with fair approximation to real gases, so the laws of fluid dynamics formulated with respect to ideal fluids can be extended to real fluids by taking into account factors that vary from fluid to fluid.

An ideal fluid does not resist changes in form; its particles do not exert on each other any tangential forces against movement. Any arbitrarily chosen element of surface within the fluid will be subjected only to a force acting perpendicularly to the surface, and the magnitude of the force depends on the pressure at that point. However, this is not the case with real fluids, for real liquids—and to a limited extent, real gases—are viscous. They oppose resistance to the relative motion of the particles, and this resistance may vary in degree. Therefore, they also display some resistance to changes in form and to the movement of the fluid itself. When one layer of a fluid is made to slide over another, each will exert an action against the other in opposition to this relative movement; that is, a tangential force will come into play to act against the sliding motion. This phenomenon is quite similar to what occurs in an elastic body, but of lesser magnitude.

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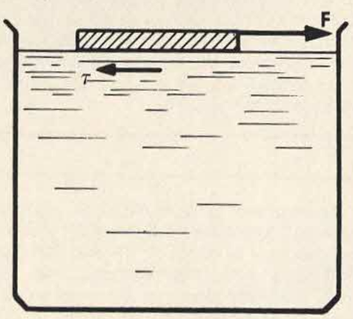

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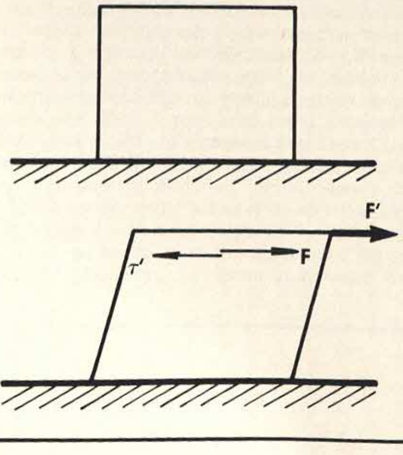

In Illustration 1a, a small board is shown floating on the surface of a liquid within a container. A force **F** is applied to the board, moving it to the right; as it moves, although its lower surface is quite smooth, it will drag along a layer of the liquid with which it has direct contact. This first layer of liquid will similarly drag the layer immediately beneath it, and so forth. Among the succeeding layers, however, will come into play a tangential force τ opposed to **F,** with a tendency to oppose the force applied.

Illustration 1b is a sketch of an elastic parallelepiped (a body with six sides, the faces of which are parallelograms), the lower face of which is fixed to a plane. If a force **F′** is applied from the left against the upper edge, the body will deform as shown in the lower section of the sketch; if the body is homogeneous, a sliding deformation will occur between one layer and another. Within the body, however, between adjacent layers, a tension τ' will come into play in opposition to the deforming action of **F′.**

The two phenomena just described differ substantially in one respect: in elastic solids, the internal tangential stress is proportional to the sliding deformation, the ratio between these two quantities giving rise to a characteristic constant known as the elastic modulus in shear. In fluids, on the other hand, the internal stress is proportional to the speed with which the successive layers slide over each other, rather than to the actual amount of the sliding, and in this case the characteristic constant relating to the speed of the stress is known as the coefficient of viscosity. The state of tension caused by the viscosity depends, therefore, on the state of motion and does not exist in a state of rest. The static equilibrium of fluids is thus in no way influenced by their viscosity, which only becomes operative when fluids are in motion.

2

LAMINAR FLOW AND TURBULENT FLOW—Inasmuch as viscosity is dependent on the motion of fluids, a study of a simple type of motion will clarify the concept of viscosity.

When a liquid flows through a pipe, for example, the resulting phenomena depend not only on the form of the pipe, but on such factors as the velocity of the liquid, its pressure, and the variation of velocity and pressure in time—all of which may be defined as the regime of the flow. If a flow is characterized by constant velocity, pressure, and discharge (volume) at any point within a given unit of time, a regime of steady flow exists. In such a regime, the various particles of the liquid and the various layers follow regular paths side by side; the flow occurs in fluid layers or lines—streamlines. The Irish physicist Osborne Reynolds conducted an experiment that is easy to repeat:

Take a large glass container with an opening on one side, and insert an open-ended glass tube horizontally into this opening (Illustration 2a). Fill the container with water and allow the water to flow freely into the tube. Now place a small glass nozzle in front of the opening of the tube and allow water from another source to flow through this nozzle; the water now introduced should be colored, so that its flow can be distinguished. As the stream of colored water flows out through the tube, it will not mix with the other water, but will flow in a thin stream of its own; all its particles will follow a path through the water in the container. (A very thin layer of liquid flowing along an inclined surface or a stream within a capillary tube will act similarly.) A flow of this kind, in which the particles slide along parallel to one another, is described as a laminar or streamline flow. If a fluid is at rest and an object of suitable form is moved through it, a comparable laminar flow will occur. If the object has precisely the right form and moves without excessive speed, the layers of the liquid will separate as it approaches, follow its outline, and come together again as soon as the object has passed.

Illustration 2b is a photograph of a model of an aircraft wing (an airfoil) immersed in a fluid stream, showing how the particles of the fluid separate and come together in laminar flow.

In practice laminar flow occurs only under especially favorable conditions; in most cases the flow is turbulent. If the speed in the tube is increased, the colored stream of water will become turbid almost immediately (Illustration 2c). Above a certain velocity, which was discovered by Reynolds, a flow loses its streamlined character and becomes turbulent, the particles following continually varied paths; eventually the colored water diffuses throughout the entire mass of liquid. Such a regime is designated one of turbulent flow. It is exemplified by the agitation of the water in the vicinity of the motorboat in Illustration 2d.

Turbulence also occurs when a solid moves through a fluid at excessive speed, or when the solid has a form that is not really streamlined. Illustration 2e shows the same streamlined airfoil shown in Illustration 2c but moving at a different angle; Illustrations 2f and 2g show two objects that are not streamlined at all. In each instance considerable turbulence appears. In the air, turbulence causes vibration and shaking and is very dangerous to the wings of aircraft. For this reason, the wings of supersonic aircraft are always very thin and suitably streamlined (Illustration 2h).

In studying these phenomena, Reynolds demonstrated that both laminar and turbulent flow regimes can occur under the same qualitative circumstances, depending on whether certain factors that determine the flow—speed, volume, viscosity—are below or above a certain critical value. Reynolds also demonstrated that laminar or streamlined flow can be maintained or produced more easily if certain precautions are taken. In a converging pipe, for example, where the velocity increases in the direction of the flow, laminar flow is more easily maintained than in a pipe of the same

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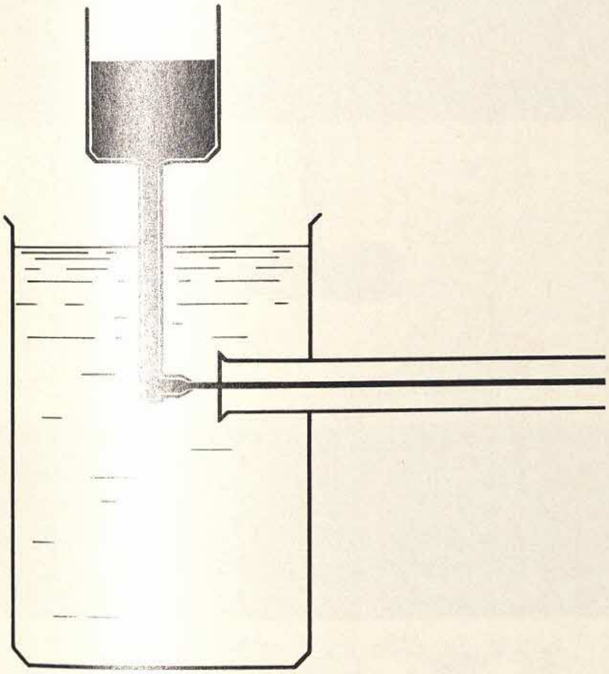

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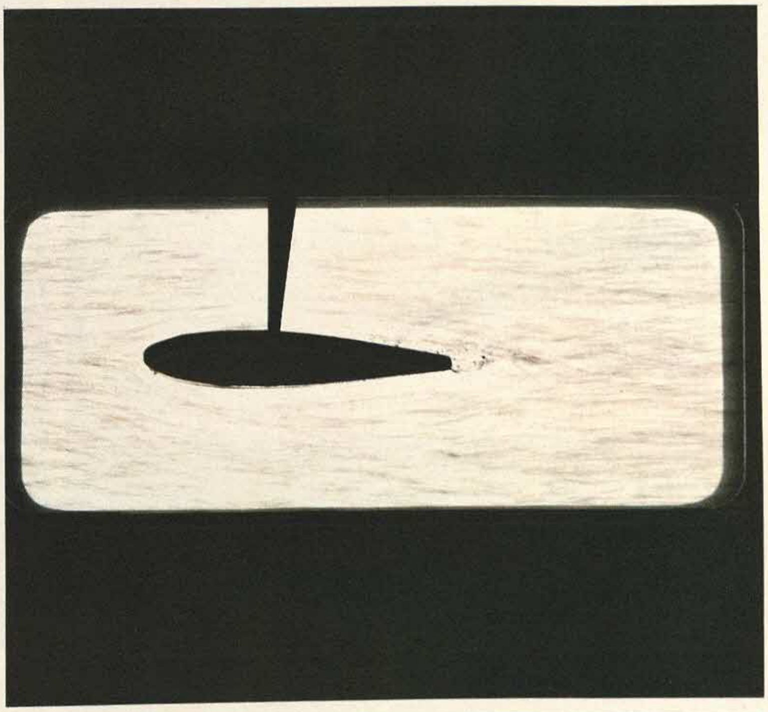

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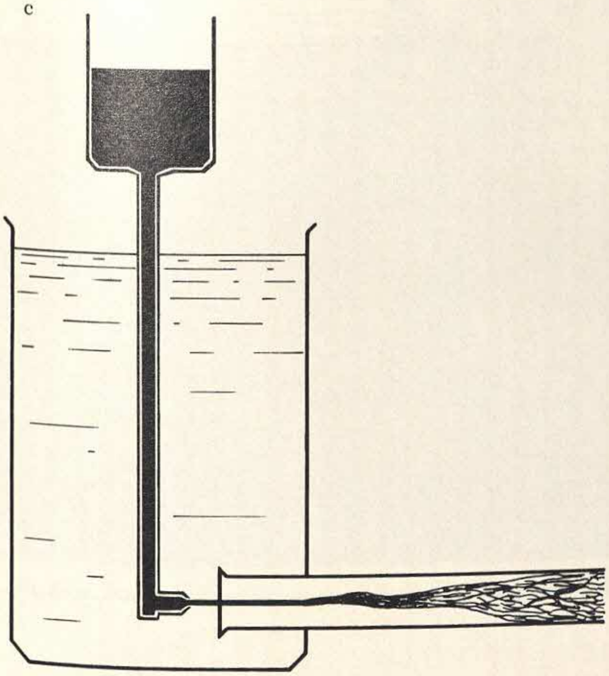
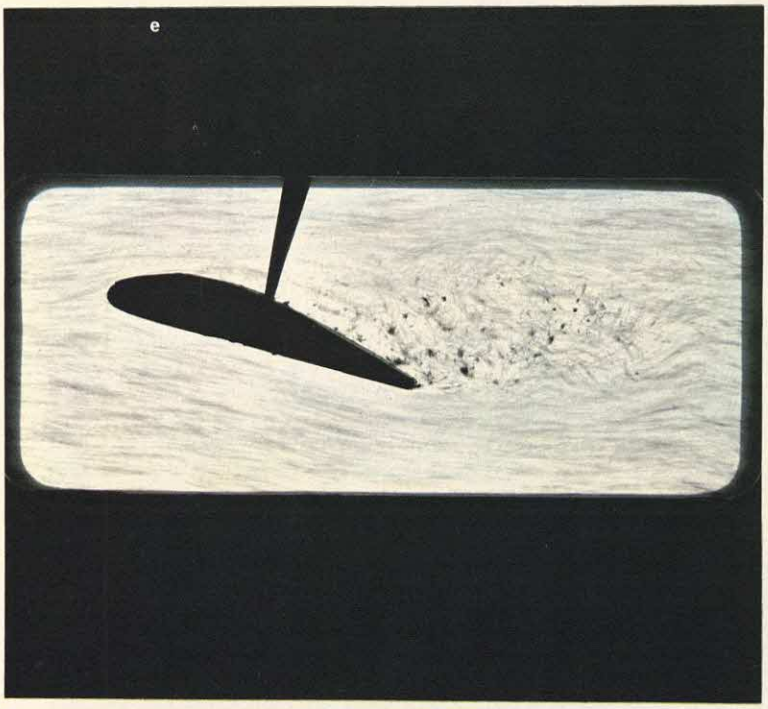
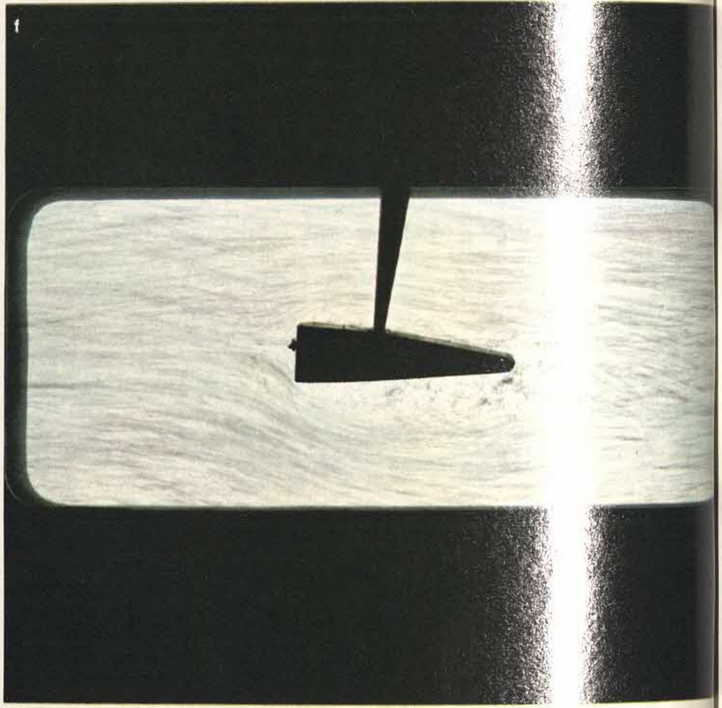
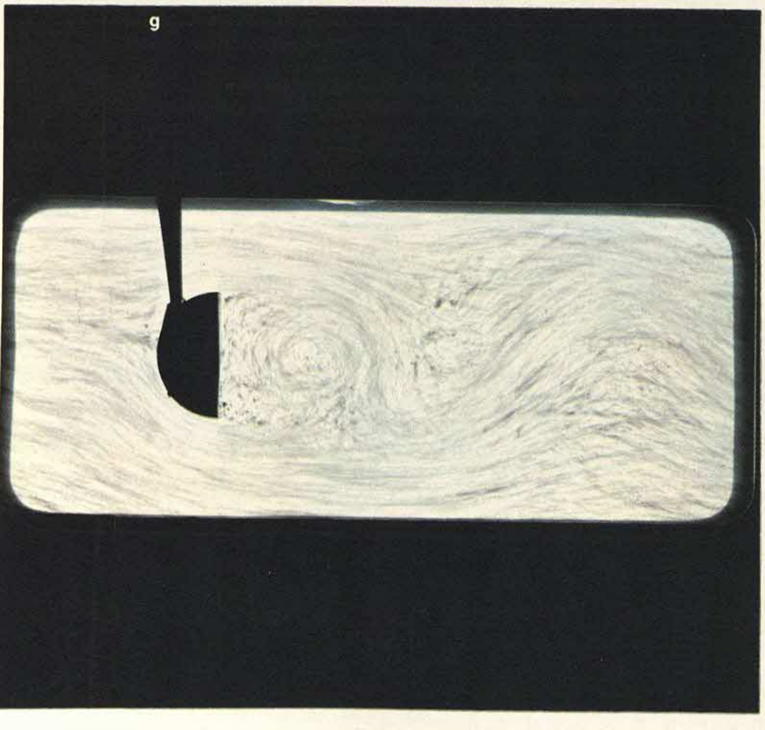


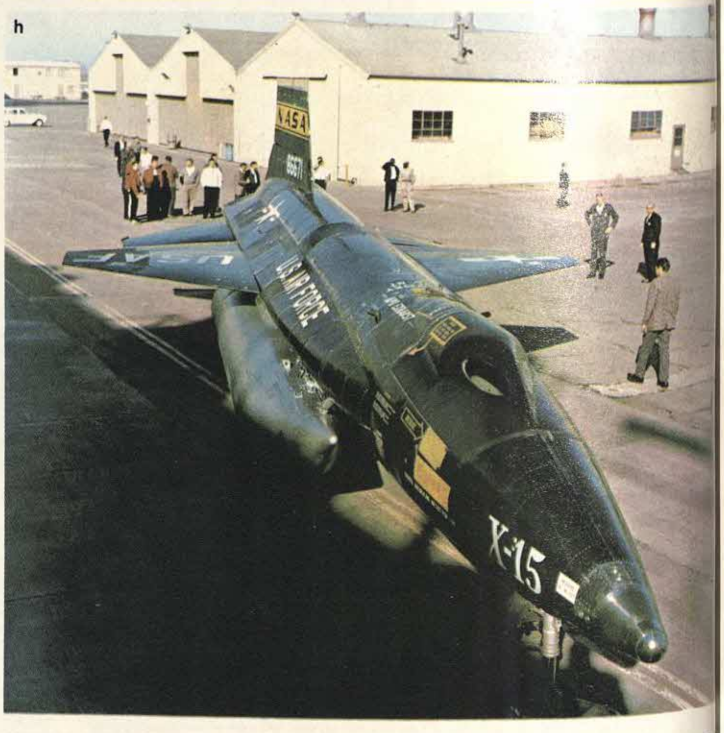
d

diameter throughout its length. However, when the pipe diverges (increases its diameter), turbulent flow will more easily be produced. Both regimes of flow can easily be observed by merely turning on an ordinary water faucet; if the water is allowed to issue very slowly, the stream is quite homogeneous; there is no spray, and the stream maintains its shape until it strikes some obstacle. When [illegible] faucet is opened more widely, a stream of water issues forth turbulently, with irregular spray and violent splashing.





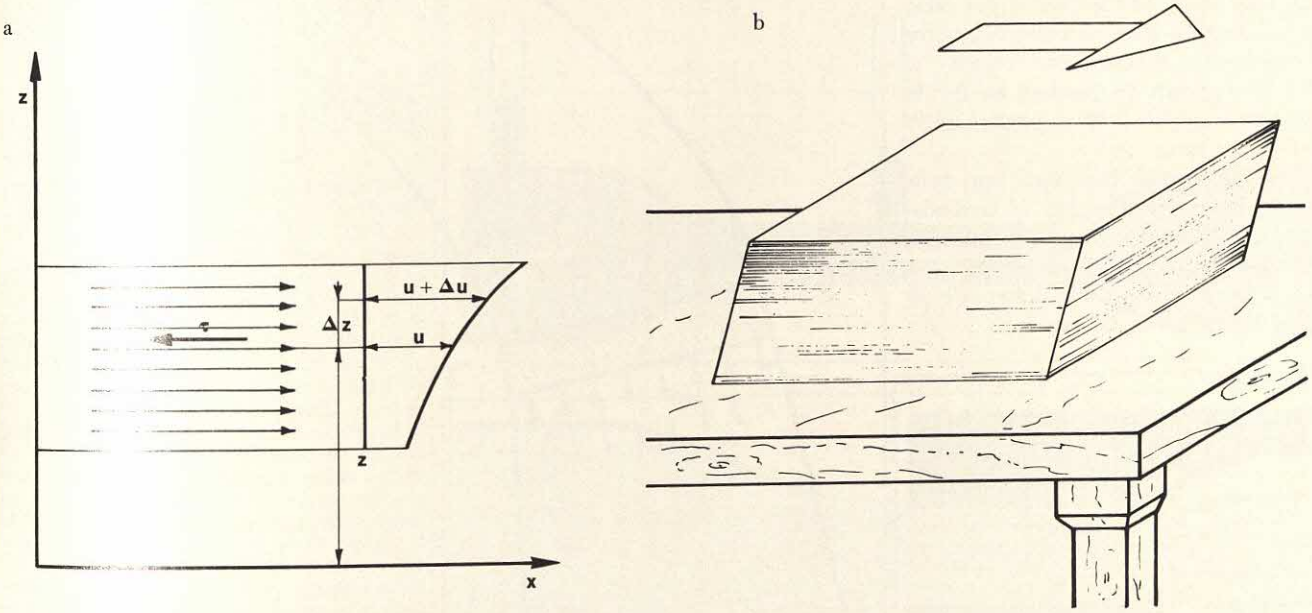




3

PETROFF'S LAW—In laminar flow only relative sliding occurs between parallel layers of the liquid, always in the direction of flow. The simplest example can be described through a Cartesian coordinate system as shown in Illustration 3a, with the **y** axis perpendicular to the plane of the page. If the flow of the liquid is only in the direction of the **x** axis and the velocity is so distributed that all the particles in any plane parallel to the plane **xy** (at right angles to the width of the page) always flow at the same velocity, then this velocity is a function of z alone and will vary according to the distance of the particle from the plane **xy**. The motion of the fluid may be compared to a stack of very thin sheets of paper that slide over each other (Illustration 3b) in the direction of the x axis (to the right of the page); the variation of speed from one layer to the next may obey any law whatsoever, provided that the variation is continuous. If two layers that are very close together are considered—layers having the respective coordinates **z** and $\mathbf{z + \Delta z}$, for example—the velocities of the two layers will be **u** and $\mathbf{u + \Delta u}$. The limit of the ratio $\frac{\Delta u}{\Delta z}$ as Δz tends toward zero (that is, as layers that are progressively thinner and thinner are considered) represents the rate of change of the velocity function with respect to the **z** axis at any particular point **z.** It is written $\frac{du}{dz}$ and is called the derivative of the speed with respect to **z.** This sliding, just as in elastic solids, causes a tangential stress τ, which acts between adjacent layers parallel to the **x** axis. The value of this stress is proportional to the sliding speed of the particular layer to which it refers; that is, to the rate $\frac{du}{dz}$. This yields the following relation for a unit surface: $\tau = \frac{\mu du}{dz}$. The coefficient of proportionality μ is none other than the coefficient of viscosity, generally termed the poise, after the French physiologist Jean Louis Marie Poiseuille. The formula is linked with the name of Petroff and gives at the same time the physical law of viscous resistance and the definition of the coefficient of viscosity.

The stress τ has the characteristics of friction acting within the mass of the fluid; in other words, a resistance against the flow of the fluid.



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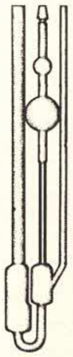


MEASURING VISCOSITY—The poise, the unit of viscosity, has the dimensions of mass divided by length and time. The coefficient of viscosity has a specific value for each fluid and for each state of the fluid, according to variations of temperature and pressure. The poise is defined as the force, in dynes, needed to move 1 cm^2 of a surface across the top of a liquid layer 1 cm thick, at the rate of 1 cm/sec. In liquids an increase in temperature diminishes the viscosity, but an increase in pressure augments it. These corollaries are especially important in the study of lubrication. Viscosity is usually measured with viscometers, of which there are various types. They are, for the most part, made in such a way as to produce a laminar flow in the fluid under examination; the coefficient of viscosity can be obtained by observation of this flow. A simple kind of laminar flow can be produced in various ways with capillary tubes or special devices. The illustration shows a type of viscometer typifying the capillary tube method. The viscosity is obtained indirectly by measuring the pressure needed to force the liquid through the small tube, the tube dimensions, and the rate of flow.

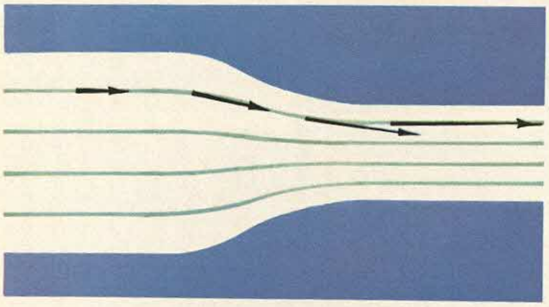
Another type of viscometer consists of two coaxial cylinders of slightly different diameters. The fluid to be examined is placed in the space between the two cylinders, and the inner cylinder is then rotated; the fluid will begin to drag the outer cylinder, and after a time this cylinder will also begin to move. The torque moving the outer cylinder is measured, and inasmuch as all the geometric constants of the instrument are known, Petroff's formula can be used to find the coefficient of viscosity. Viscometers of this type, called absolute viscometers, do not need to be calibrated; the viscosity can be obtained directly from the laws of fluid motion.

THE STEADY FLOW OF FLUIDS

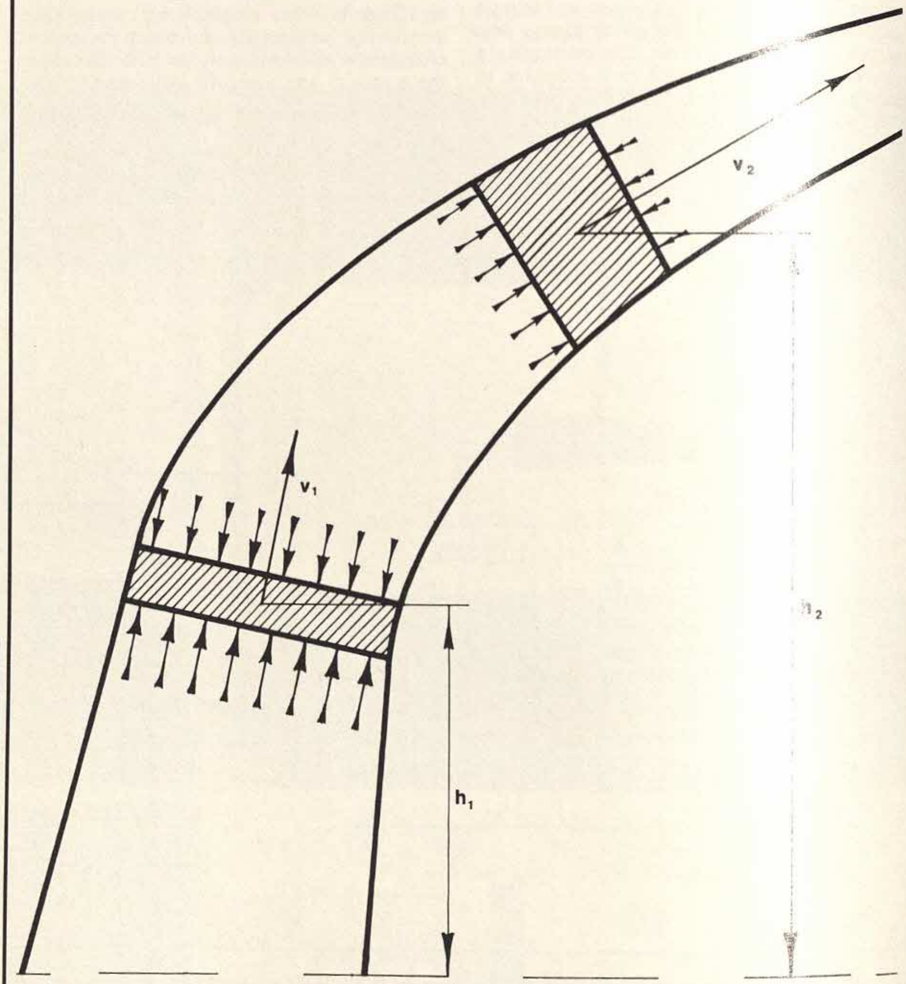
Bernoulli's principle

One of the primary fields of inquiry in the science of hydrodynamics deals with the characteristics of fluids in steady flow, a form of motion in which the component particles always pass a given point at constant velocity. When a faucet is opened and the water issues freely, for example, it soon flows steadily, and passes any point along the pipe leading to the faucet outlet at a constant velocity. This would be the case at any other point along the water pipe leading to the same faucet, although the velocity at two given points (depending on the diameter of the pipe at those points) might not be the same.

Conclusions of this sort are quite important in all branches of hydrodynamics, including hydraulics, which deals with water and other liquids in motion, and aerodynamics, which deals with air and other gases in motion.



THE BEHAVIOR OF FLOWING FLUIDS—In this section of pipe, the velocity of the liquid varies from point to point because the diameter of the pipe varies. Instead of dividing the interior volume of the stream within the pipe into a number of small volumes and analyzing the velocity of the liquid within each of these volumes, scientists measure the flow of the liquid by streamlines—lines drawn in such a way that the velocity of the liquid at any one point is always tangential to the streamline passing through that point; the velocity increases as the diameter of the pipe decreases.



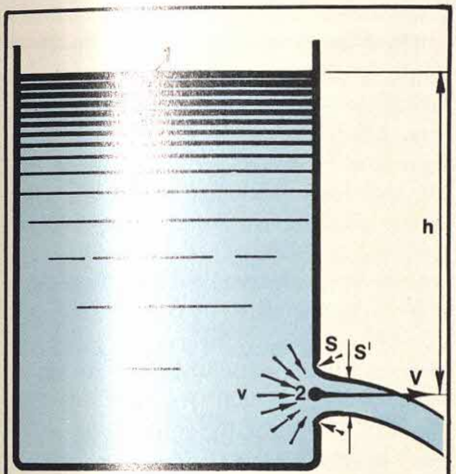
BERNOULLI'S PRINCIPLE—A fluid in steady flow may be analyzed in respect to three quantities: the velocity of particles in its stream; its pressure; and its head—the vertical distance of the particles under consideration in relation to some point of reference. In the illustration, a liquid is flowing upward in a pipe of varying diameter, bent at a slant away from the base. Near the bottom of the pipe, at the height $\mathbf{h}_1$ above the base, is a shaded strip representing a cross section of the stream of flow, at which point the velocity is $\mathbf{v}_1$; the two series of arrows indicate opposing pressures acting on the stream. The constriction of the pipe's diameter, the bend in the pipe, and the force of gravity in combination are shown to have altered the forces acting on the particles in the stream at the next cross section (at a height $\mathbf{h}_2$), changing their velocity ($\mathbf{v}_2$) and their pressure.

Daniel Bernoulli, a Swiss mathematician, formulated these observations in a famous law of the conservation of energy as applied to fluids in steady flow. The law states that the sum of the energy of velocity plus the energy of pressure plus the potential energy resulting from elevation is a constant, so that if any one component varies, the others will vary accordingly. This is expressed in mathematical terms as follows:

$$p + \frac{dv^2}{2} + dgh = K$$

where p is the pressure; d is the density (in some formulations, m for mass is used); v is the velocity; g is the acceleration of gravity; and h is the height.

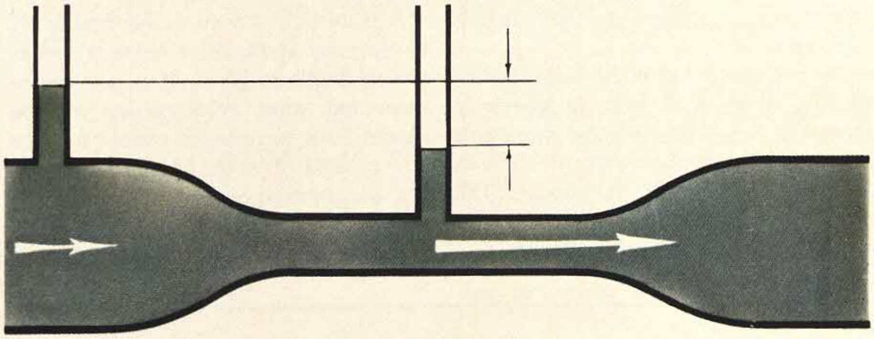
Assuming that the factor of elevation and potential energy is not involved, an increase in the pressure would result in a proportional decrease in the velocity, and vice versa. Translating this principle in terms of the present example, as the pipe becomes narrower (the flow remaining steady), the volume of the fluid would have to pass a given length of pipe with increased velocity; therefore, in this length of pipe, the pressure would decrease. When the stream of fluid enters a pipe with larger diameter, the velocity would diminish, and the pressure would increase. This principle has practical application, as in the flow of air above and below an airfoil, which is so constructed as to develop lower pressure above the foil than below it, and so provide lift to the airplane wing.

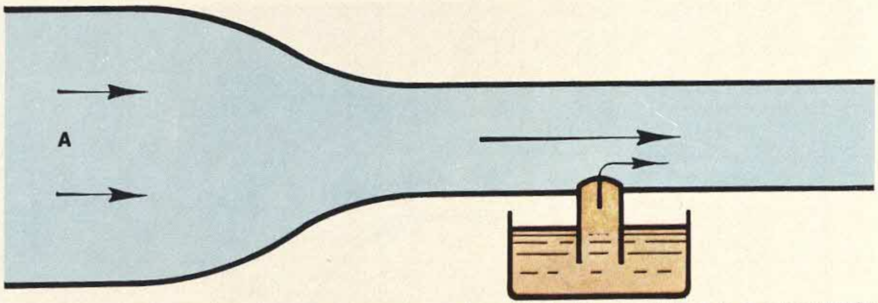


TORRICELLI'S THEOREM—One application of Bernoulli's principle is known as Torricelli's theorem, postulated by Evangelista Torricelli, an Italian physicist who lived almost a century earlier than Bernoulli. This theorem concerns the velocity with which a liquid flows from a subsurface outlet in a container. The illustration shows a container filled with water that flows from an outlet near the base of the container. A particle of water at the point on the surface of the liquid **1** is at rest, and subject only to atmospheric pressure. On the other hand, a particle of liquid approaching the outlet **2** is already moving at a certain velocity. Torricelli demonstrated that the velocity of this particle as it passes through the outlet is the same as the particle would have if it were to fall freely through a vacuum for the vertical distance **h** from the surface of the liquid to the outlet. This is expressed mathematically as $V = \sqrt{2gh}$.

As the illustration shows, the stream of the liquid as it leaves the container through the outlet diminishes in cross section once it has left the container. This results from the convergence of the particles in the fluid directly in front of the outlet, a convergence shown by the arrows. Each particle is directed at the center of the outlet; the cross section of the stream at **S'** is about two thirds that of the cross section at **S.** If the stream continued to fall freely without being disturbed by turbulence or surface tension, it would continue to narrow and its velocity continue to increase.

THE VENTURI TUBE—This device, invented by an American engineer, Clemens Herschel, and named in honor of an Italian physicist, G. B. Venturi, also applies the Bernoulli principle. The fluid enters the wide section of the tube and passes through a narrower section; according to the Bernoulli principle, its velocity will increase and its pressure will decrease in the narrower section of the tube. If a hole is made in the top of each section of the main tube, and secondary tubes are joined perpendicularly to the main tube at these two places, as shown, the fluid will rise to a higher level in the tube joined to the wide section than in that joined to the narrower section. Devices of this kind are inserted into a tube or pipe system to measure the flow of a fluid; in such cases, they are called Venturi meters.





SUCTION PHENOMENON—Another manifestation of Bernoulli's principle and the Venturi tube is shown here. It is assumed that air (which is a fluid) is forced at atmospheric pressure through the wide section of the tube **A** and that its pressure is reduced as it enters the narrower section. If a hole is made in the bottom of the main tube in the narrower section, and the tube is connected with a container filled with a liquid that is at atmospheric pressure, the reduced pressure of the passing stream of air will cause the liquid to be drawn up through the hole. One application of this device is the venturi in the automobile carburetor, the constricted passage where the air pressure is reduced to draw in the necessary amount of gasoline from the float chamber.

It is customary in fluid mechanics to regard fluids as continuous media. Actually, gases and liquids consist of molecules and atoms. Fluid properties and actions are directly related to molecular behavior. In most cases of flow, however, the mean free path of the molecule is small in comparison with the distances involved; thus the flow actions can be studied by reference to bulk properties.

Daniel Bernoulli and other mathematicians constructed their theories of flow around the concept of an "ideal" continuous fluid having no viscosity. It is interesting to note that their mathematical formulas produced results remarkably close to those observed in actual fluids under modern experimental conditions.

FLUID DYNAMICS | the foundations of fluid mechanics

The properties of fluids in motion have intrigued man since the time of Aristotle and Galileo. Called fluid dynamics or hydrodynamics, the branch of physics dealing with such properties explains a great many natural phenomena.

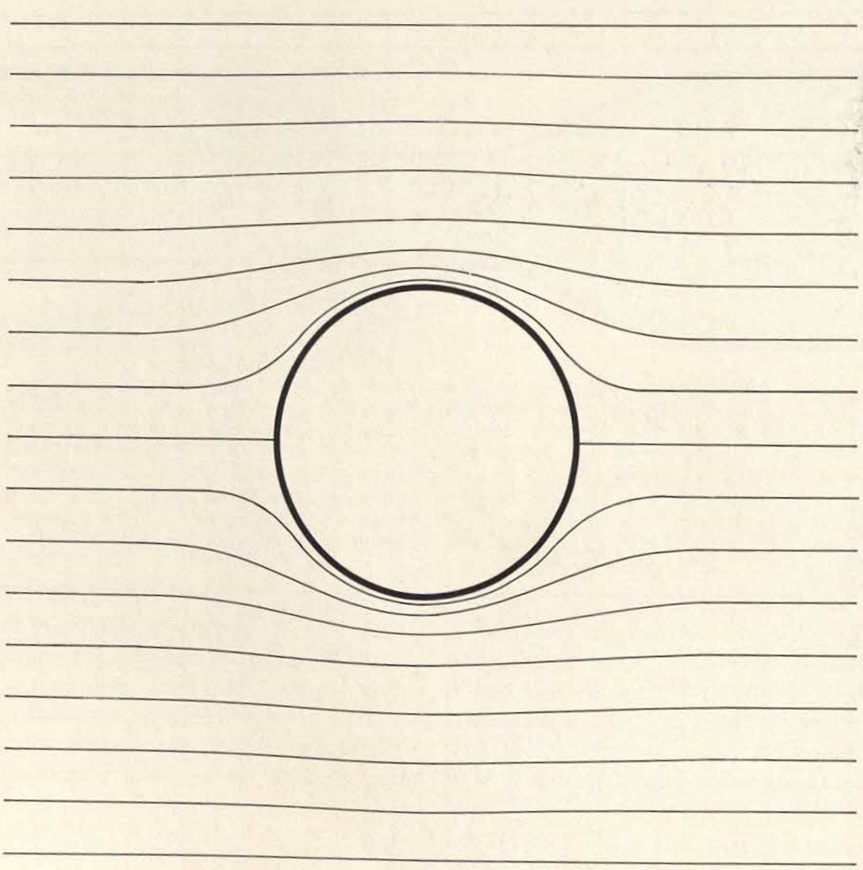
Fluids, in this sense, are those substances not in the solid state. Water, mercury, air, and steam are some common examples of fluids. The laws of fluid dynamics are many, and are most easily understood in relation to engineering problems.

The term *fluid mechanics* includes kinematics, which deals with the geometry of motion and, thus, with the way fluids move, and dynamics, which deals with the forces involved in the motion. The term *hydrodynamics* refers particularly to the purely theoretical study of some type of flow. In fluid mechanics, it is customary to regard fluids as continuous media. Actually, liquids and gases consist of molecules and atoms; fluid properties and actions are directly related to molecular behavior. But in most cases of flow, the mean free path of the molecule is small in comparison with the distances involved, and the flow actions can be studied by reference to the bulk properties of the fluid.

A problem that occurs quite frequently in everyday applications is the transmission of fluids in pipes. It is possible to determine what cross section a pipe should have in order to sustain a given flow of fluid when the length of the pipe and the pressure on the fluid are known. Similar problems are faced by the engineer designing a steam-heating plant or a lubricating system.

The laws of fluid dynamics generally apply to ideal fluids, which means that laboratory experiments are often necessary before a problem involving real fluids can be solved. However, some of the laws formulated for ideal fluids can be extended to real fluids simply by introducing variable parameters that characterize the particular fluid being studied.

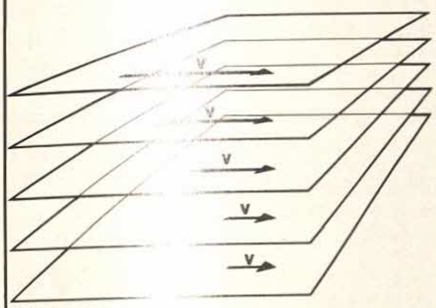
In studying fluid dynamics, the researcher is often in the curious position of having to construct many of the laws by neglecting certain characteristics of fluids. Viscosity, or the ability of a real fluid to resist internal flow, is a prime example of this. An ideal fluid, on the other hand, has no viscosity and any solid body could move through it without encountering resistance or friction.



THE IDEAL FLUID AND D'ALEMBERT'S PARADOX—An ideal fluid is understood to mean a fluid that is absolutely incompressible and wholly devoid of internal friction (that is, totally without viscosity). Such a fluid does not exist, but some real fluids can be considered nearly ideal. However, in the present case, regarding the relative motion between a fluid and a solid body, the ideal fluid will lead to erroneous considerations.

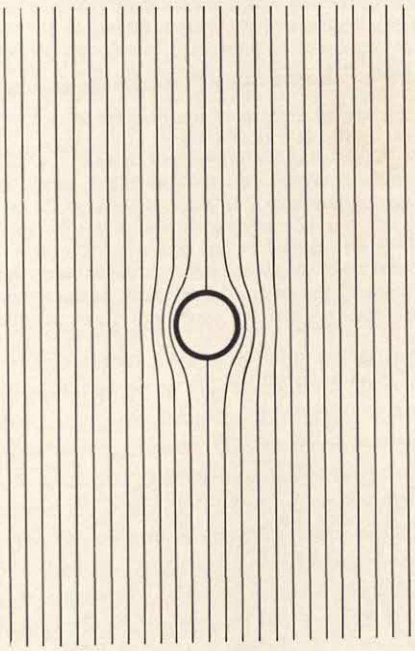
Consider the sphere in this illustration. A fluid is flowing past it without forming vortices (streamline flow). Each particle of the fluid flows along the lines shown, or along intermediate lines that can be easily interpolated. The fluid exerts a pressure on the front of the sphere because the sphere forces the fluid to change direction. Nevertheless, after having passed the sphere, the fluid returns to its original direction of flow because the sphere now exerts a contrary pressure on the fluid particles. The total field of pressures exerted on the sphere is thus zero, and the sphere is not, therefore, subject to any pressure at all. This means that when the sphere is immersed in an ideal fluid in streamline flow it is not subject to any forces and does not offer any resistance.

This conclusion, known as D'Alembert's paradox because it clearly contradicts reality, is an important starting point when defining real motion. In studying motion, it is not important whether the fluid is at rest and the body moving, or the reverse, for all motion is relative. For example, a ship model can be tested by holding it stationary in a tank of moving water, or by moving it in a tank where the water is at rest.



STREAMLINE FLOW—The term streamline or laminar flow is used quite often when discussing fluid motion. It means that the particles of the fluid all flow along parallel paths, which are again placed on parallel planes, or surfaces. The velocity v of the flow along a trajectory on one surface may differ from the velocity on an adjacent surface, as shown. In any case, no vortices may occur in any part of the space that is subject to streamline flow.

An example of streamline flow is shown in the illustration on p. 128. The surfaces that contain the streamlines are separated by variable distances; as the distance increases, the speed diminishes, and vice versa. A vortex may also appear at some point between the surfaces, meaning that the streamline flow has given way to turbulent flow.



FLOW COVERED BY FRICTION—A body moving through a real fluid will encounter a resistance that is due to various causes. When the motion occurs at very slow speeds, the body will be under conditions rather similar to those of D'Alembert's paradox, at least according to the streamlines, or paths followed by the particles of the fluid.

In this illustration, the streamlines are those of a small sphere falling in air. Since all motion is relative, it makes no difference whether the sphere is considered to be falling, or the fluid (air) to be moving upward. Near the sphere, the layers slide over each other at a small relative speed that must be considered. Resistance or friction is exerted between these surfaces. The particles in contact with the sphere will be dragged along by it; thus they can be considered at rest.

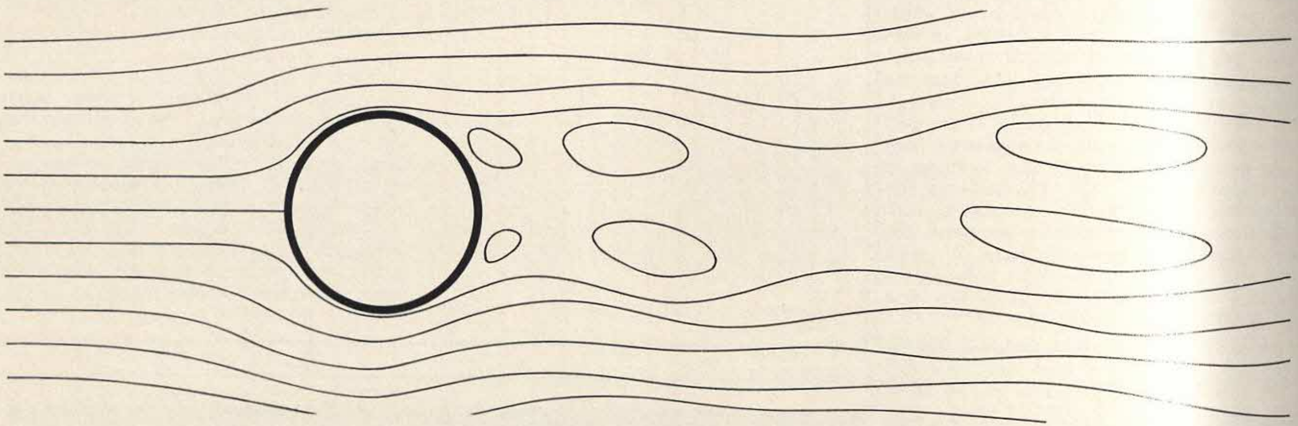
The friction between this immobile fluid layer and the adjacent layers in motion has the effect of transferring a part of the translation energy of the sphere to these mobile layers. In other words, the sphere gives up some translation energy to the fluid by dragging it along, or the fluid resists the motion of the sphere. This force, the result of internal friction between surfaces of the fluid (viscosity), characterizes the type of flow that is said to be governed by friction. In this type of flow, resistance is proportional to the velocity and linear dimensions (shape) of the body immersed in the fluid.

STOKES' LAW—The drops of water that form clouds are a typical example of flow (or motion) caused by friction. The size of the drops can vary over a wide range (as in clouds, fog, drizzle, and heavy rain). Nevertheless, only the smallest drops, as in clouds, are in a state where their falling motion is governed by friction. The velocity of these drops is so small that even a slight turbulence, or a very weak current of air, is sufficient to ensure they will not fall but will remain suspended in air in the space occupied by the cloud.

It is very important to be able to establish the velocity of a falling object (sphere), and especially the forces that will act on it at different velocities. It can be demonstrated that the force F acting on a small sphere moving in a fluid is $F = 6\pi r v \eta$, where v is the velocity of the sphere, r is its radius, and η is the coefficient of viscosity. Assuming that the particle is free to fall, its velocity (originally zero) will increase until the resistance equals the force that makes it fall; that is, the weight of the particle itself. The steady falling speed of the particle can be determined by Stokes' law: $V = 2r^2g(d - d_0)/9\eta$, where d and d_0 are the densities of the sphere and the fluid, and g is the acceleration due to the force of gravity (9.8 m/sec^2).

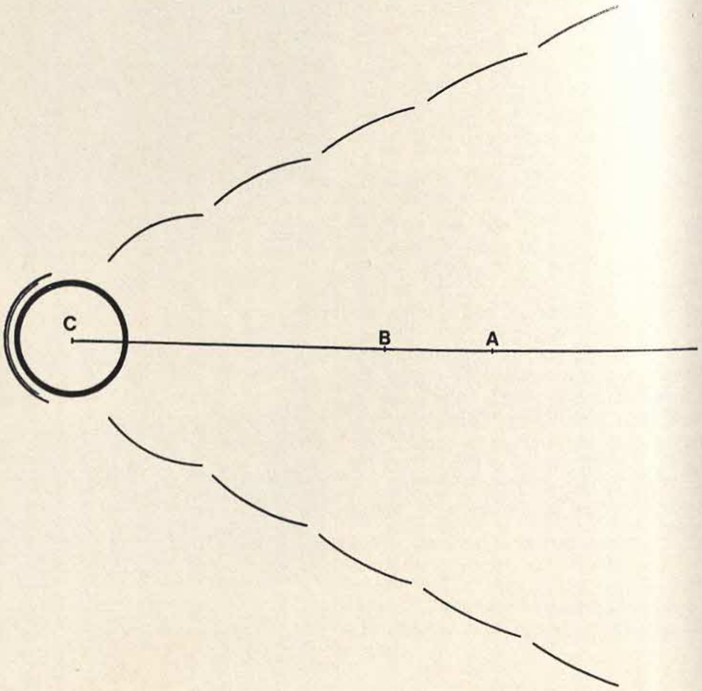
FLOW GOVERNED BY PRESSURE—Any solid body moving through a fluid at a sufficiently low speed will remain in conditions where its motion is governed by friction resistance. These same conditions will change when a certain speed is exceeded, however. When the body attains a certain velocity (depending on several factors, including shape and size), the motion of the fluid around it will no longer be a streamline flow. Vortices are formed as the body passes, and part of the fluid is dragged along by the body, thus transferring kinetic energy from the body to the fluid itself. In this condition, the fluid no longer exerts a symmetrically distributed pressure on the body. Instead, the pressure distribution is unsymmetrical and the body is subject to a force of resistance in proportion to velocity. In this case, the resistance exerted on the body is proportional to the square of the velocity, and the internal friction of the fluid no longer has an appreciable resistance.

This law can be written as $F = k\pi R^2\ (\mu V^2/2)$, where F is the resistance, R is the radius of the sphere, and V is the relative velocity between the fluid and the sphere. In this formula, μ is the density of the fluid while k is a coefficient of proportionality that depends on the shape of the body. The influence of the shape is important and the coefficient k can assume widely differing values, even in those cases where the cross section of the body remains unchanged. (The fundamental problem of aerodynamics is that of determining the shapes required in order to move rapidly through the air in such a way as to keep the coefficient k to a minimum, while at the same time allowing other aerodynamic coefficients, such as lift, to assume the desired values.) In any case, these conditions of flow are characterized by a resistance in proportion to the square of the velocity. While this law is not perfectly valid for all values of the velocity, it does give reasonably accurate results up to the speed of sound.



SUPERSONIC SPEED—At supersonic speeds, a sphere moving through air must displace air in front of it as it moves forward—just as in streamline and turbulent flow. However, the displacement occurs much more rapidly than the propagation of the compression disturbance. As it passes point **A** the body generates a compression wave in front of it; that is, a wave that is beginning to spread. It is shown here after attaining certain dimensions. Later, as it passes point **B,** the same body will generate an analogous disturbance in the surrounding air. Finally, the body will reach point **C,** where it is shown displacing the air in front of it. In this example, the sphere has generated a succession of compression waves arranged to form a cone-shaped surface (shown as a V because it represents a section through the cone).

These conditions of flow are called supersonic conditions and are characterized by the fact that the resistance opposing the motion of the body grows faster than the square of the speed with which the body is moving through the fluid.



THE LIQUID STATE | molecules in comparative freedom

The physicist probes the unknown. He continually knocks on the door of disorder, anxious to peek into an area of what seems chaotic disarray; for he wants to see if he can discover in disorder some kind of logic and order. He asks the right question and searches out the correct answer. Molecules, for example, act and react in innumerable ways. But just how do they manage in certain circumstances to form a liquid rather than a solid or a gas? The answer is as fascinating as it is intricate.

A characteristic feature of gas molecules is a disorderly thermal movement. When this movement diminishes and these particles lose their kinetic energy, the cohesive force between molecule and molecule gains the upper hand: the molecules attract each other, they become concentrated in space, and the substance liquefies. Passage from the gaseous to the liquid form is called condensation. The substance's newly assumed liquid state is characterized by a cohesive force. However, this force is not weak enough to permit the free movement of the molecules in space (which happens in the case of gases); at the same time it is not sufficiently strong to block the molecules in a well-defined position in space (which happens in the case of solids).

In a liquid substance, the molecules continue to move due to thermal action, but their movements are no longer completely unconfined. The molecules now are concentrated in a rather restricted space. They collide and touch each other with the outermost orbits of their atoms, yet they are still capable of sliding over one another, making it possible for the liquid always to assume the form of the vessel in which it is contained.

On the other hand, the considerable viscosity brought into play by the cohesive force makes certain that the relative displacement of any two adjacent layers in the liquid will always encounter a certain resistance.

The forces that oppose the free movement of the molecules with respect to each other are thus the cause of a certain internal friction existing within the liquid.

The molecules of gases, especially the molecules of rarefied gases, can travel through space for relatively long distances without encountering either the walls of a container or another molecule. However, the molecules of a liquid can carry out only rather limited displacements because the free space between one molecule and the next is reduced to a minimum. Consequently, it is very easy

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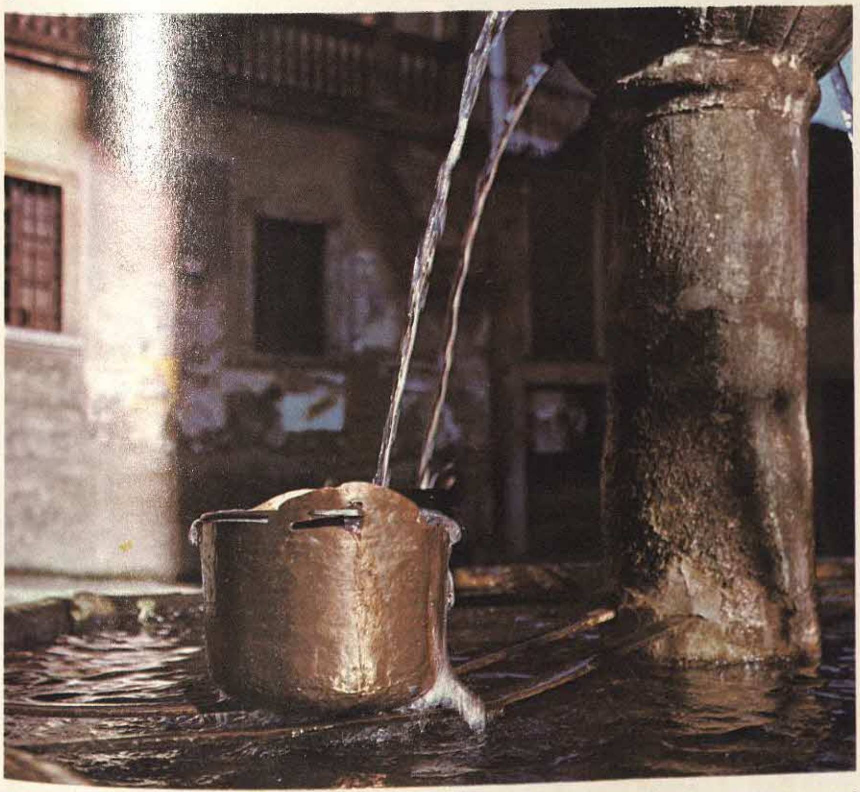


THE LIQUID STATE—This spout of water issuing from a fountain gives an indication of the cohesion that exists between the molecules of a liquid

2a

2b

WINE DIFFUSES VERY SLOWLY IN WATER—When a few drops of red wine are put into a glass of water, a few reddish clouds can be immediately observed in the colorless mass of water (Illustration 2a). If the glass is allowed to stand still and the liquid is not stirred, quite a long time elapses before the wine becomes completely diffused (Illustration 2b).

to diffuse one gas within another; but the diffusion of a liquid in another liquid takes place far more slowly. An example might clarify this concept. If one milliliter of hydrogen is put into one liter of helium, almost immediately a few hydrogen molecules will be found in every part of the volume which was previously occupied by the helium, despite the fact that these elements have different specific gravities. A different result will be obtained if a few drops of wine are placed in a glass of water, if neither liquid is agitated (Illustration 2a). Wine generally has a specific gravity slightly less than that of water; yet many hours will pass before the red color diffuses throughout the glass if it is allowed to stand still (Illustration 2b).

Another property of liquids can be discovered by considering the forces that act on a certain molecule in the midst of all the others within the liquid. This molecule is kept in perfect equilibrium by the forces existing between it and its neighbors (Illustration 3a).

Another molecule that deserves consideration is the one at the surface of the liquid, or better yet, all the molecules in this position. These molecules are attracted only by their neighbors and by other molecules farther down, for no attractive force is exerted on them from above the surface (Illustration 3b). They will arrange themselves close together and, because they are attracted toward the interior, they will press on the rest of the liquid as if to construct a film of greater density, a kind of shield for the rest of the liquid (Illustration 3c).

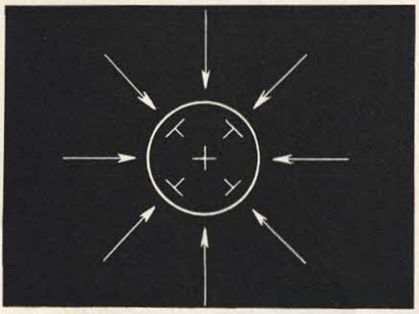
The phenomenon that leads to the formation of this surface film is called surface tension. When minute drops of a liquid are sprayed into the air, surface tension causes them to assume a spherical form. Naturally, the form of these droplets is not determined by the presence of a container. Rather, the molecules on the surface of each drop will be attracted toward the interior, and thus the surface will tend to contract into the smallest possible area compatible with the volume of the drop. This condition is fulfilled by the sphere and the drop thus assumes a spherical form, just like the dew on a leaf (Illustrations 3d and 4).

The same phenomenon can be ob-

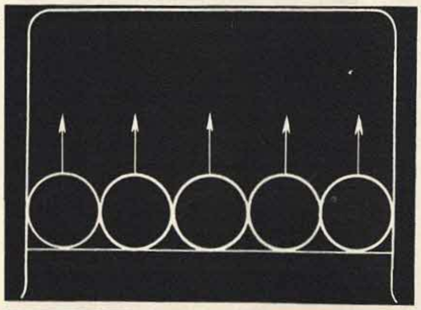
MOLECULES IN LIQUIDS—A molecule in the interior of a liquid (Illustration 3a) is in perfect equilibrium, because it is attracted by all its neighbors and these attractive forces are equal in all directions. A molecule in the surface layer of the liquid (Illustration 3b) is attracted only by the other molecules further down in the liquid; no attractive forces act from above. The surface molecules (Illustration 3c) pack closely together. Since they are attracted toward the interior, they press on the rest of the liquid, thereby constituting a dense and compact film.

Surface tension will cause any liquid sprayed into the air to assume a spherical form (Illustration 3d), because this form has the minimum surface area compatible with the volume of the liquid.

3a



3b



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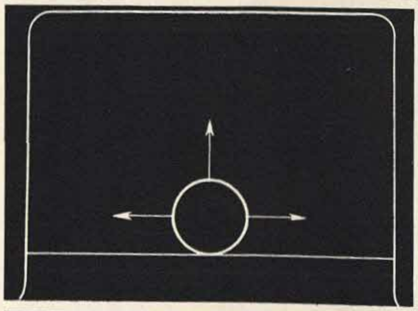
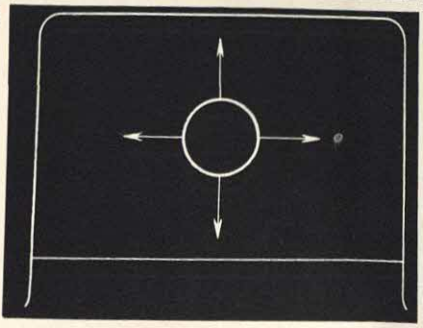


3d



THE NATURAL FORM OF A FREE LIQUID—A liquid left free in space will assume the form having the minimum surface area: the sphere. The small droplets found on a leaf after a rain are all in the form of hemispheres: the part in contact with the leaf is flat, but the free surface assumes a spherical form.

4

served when oil is placed in a liquid with which it does not mix—water, for example. The oil collects into spherical drops and remains in this form.

A high percentage of all the molecules will possess more or less the same energy: the most probable kinetic energy. Some of the molecules will move with greater energy, others with less. A few molecules, however, will have very high energies and so will move far more rapidly than the others. They may even reach the surface layer of the liquid, pierce it, and escape into the air. Whatever the liquid, some molecules that have succeeded in escaping from it will always be found above its surface. This tendency of molecules to leave the liquid and form a vapor about it is called vapor tension. Each liquid has a characteristic vapor tension, which varies according to the liquid's temperature. In fact, as the temperature rises, not only does the kinetic energy of the molecules become greater, but the percentage of molecules that succeed in escaping from the liquid to become vapor also increases.

The vapor tension of a liquid at room temperature can easily be measured. First, a glass tube, open at one end, is filled with mercury. The tube is then placed upside down into a mercury bath and supported in such a way that it will not touch the bottom. The mercury level in the tube will fall until its height above the mercury in the bath is no more than required to balance the atmospheric pressure at that moment. A small quantity of the liquid is then put into a specially prepared eyedropper whose open end is curved back. The curved end of the eyedropper is hooked into the bottom of the mercury tube and a few drops of the liquid are forced out. Since the liquid is lighter than the mercury, it will rise rapidly up the tube and reach the space left free by the fall of the mercury when the tube was turned upside down.

The substance, to the extent permitted by the temperature at which the experiment is carried out, will then emit vapor. The molecules of the vapor exert a certain pressure, and this will cause the level of the mercury to fall still farther. The difference in the mercury level before and after the introduction of the liquid expresses the vapor tension of the liquid at that particular temperature.

Obviously, the vapor tension must always be measured in the presence of the liquid phase. When the evaporation occurs throughout the whole mass and not just on the free surface of the liquid, the liquid is said to be boiling. At the boiling temperature, the vapor tension of the liquid is equal to the atmospheric pressure.

5

OIL DROPS—Any oil immersed in water collects into spherical drops that remain on the surface.

6

ON THE SURFACE OF A LIQUID—Surface tension makes it possible for many insects to rest on the surface of a liquid and for some to walk on it.

THE SPECIFIC GRAVITY OF LIQUIDS

Archimedes' principle

More than 2,000 years ago the Greek mathematician Archimedes was asked by his friend, King Hiero II of Syracuse (in Sicily), whether a certain crown of gold that the king had ordered was indeed made of pure gold or adulterated with silver. Archimedes obtained from the king a piece of pure gold, precisely the same weight as the crown, and immersed each in water. The crown displaced a larger quantity of water than the piece of pure gold, and Archimedes told Hiero he had

1

MAKING A HYDROMETER—It is not difficult to make a hydrometer, nor does the work require much time or expense. It is, therefore, possible to make a number of these instruments, until practice ensures a degree of skill. The requisites are a Bunsen burner with a moderately small flame, and glass tubes of various diameters, preferably manufactured to size—to ensure matching tubes of prescribed diameter. Moreover, inasmuch as tubes are joined in making the instrument, all the glass should be of homogeneous composition. The glass tubes should be of two sizes: 10-mm outer and 8-mm inner diameter; and 3-mm outer and 2-mm inner diameter.

First, a piece of the large-size tube is closed in a point at one end (Illustration 1a). The tube is then heated over a length of about 1 cm from the closed end; then, a bulb somewhat like that in Illustration 1b is formed by blowing into the tube. The tube is then heated above the bulb and is drawn in such a way as to form a capillary of about the same size as that to which it is to be joined—that is, with an outer diameter of 3 mm (Illustration 1c). The tube is then cut in the capillary part just above the bulb (Illustration 1d); the bulb is retained and the rest is discarded. The capillary extremity of the bulb and one end of the capillary tube are now heated in the same flame; when both parts are hot, they are joined, making sure that no obstruction results in the tube. This operation can be practiced by preparing several of these objects, each with different bulb dimensions and possibly also of various lengths and

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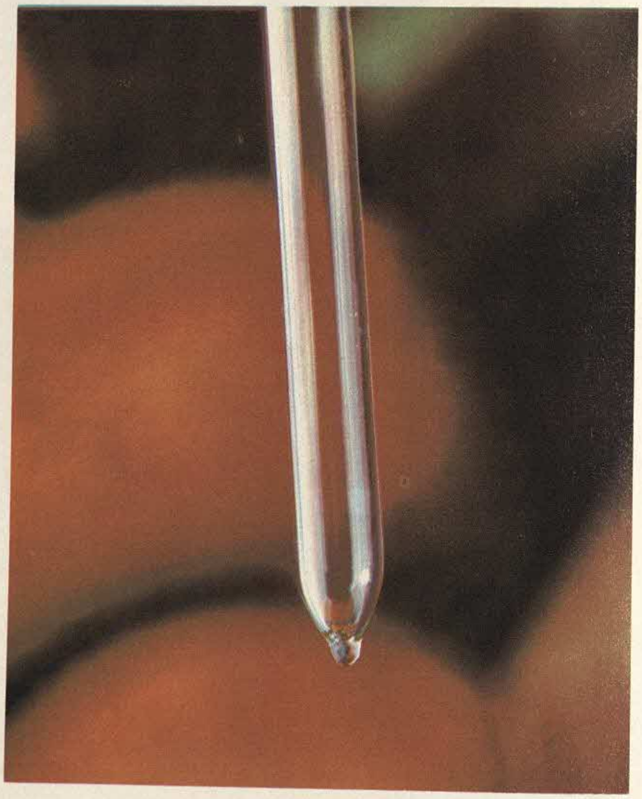

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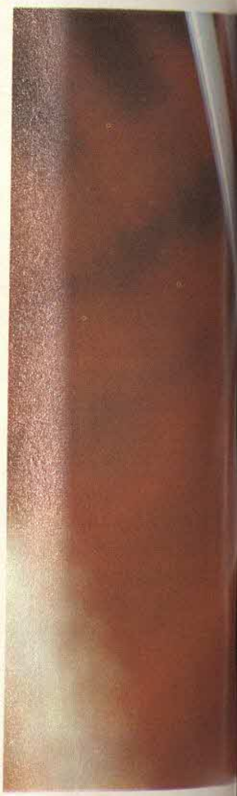

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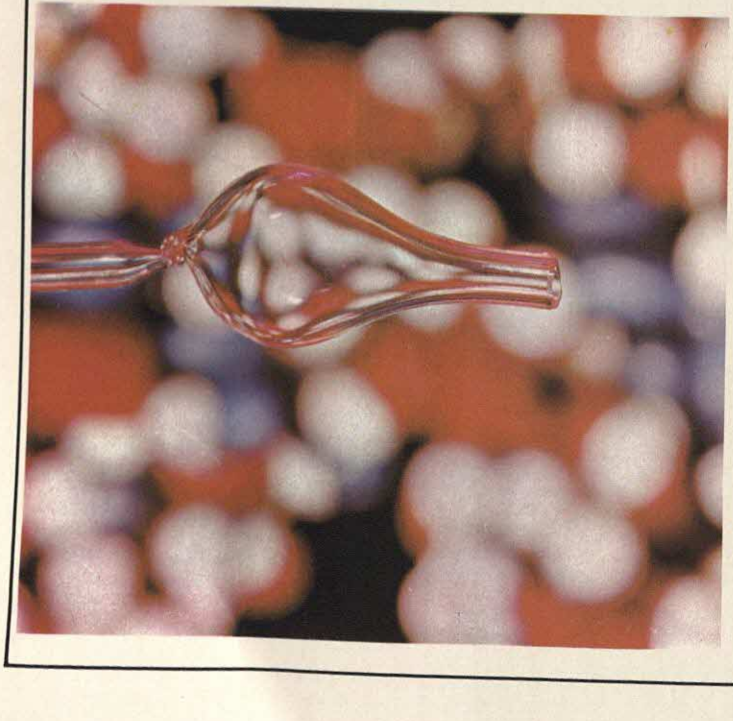
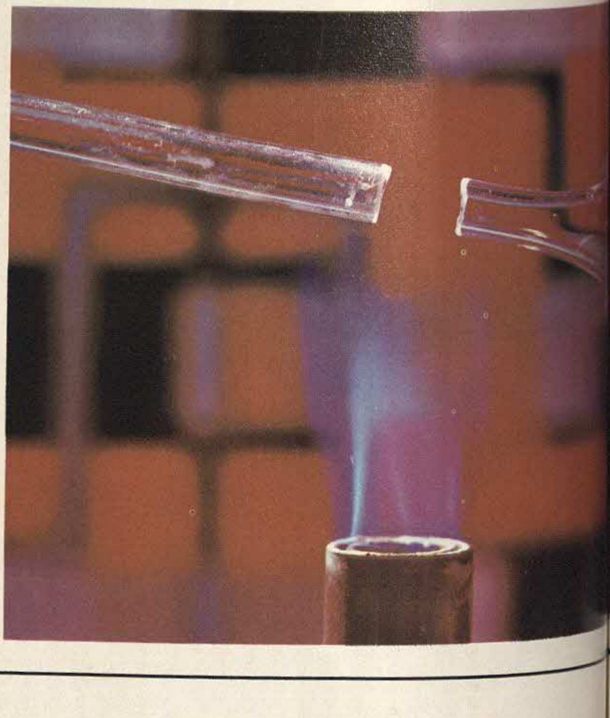


e

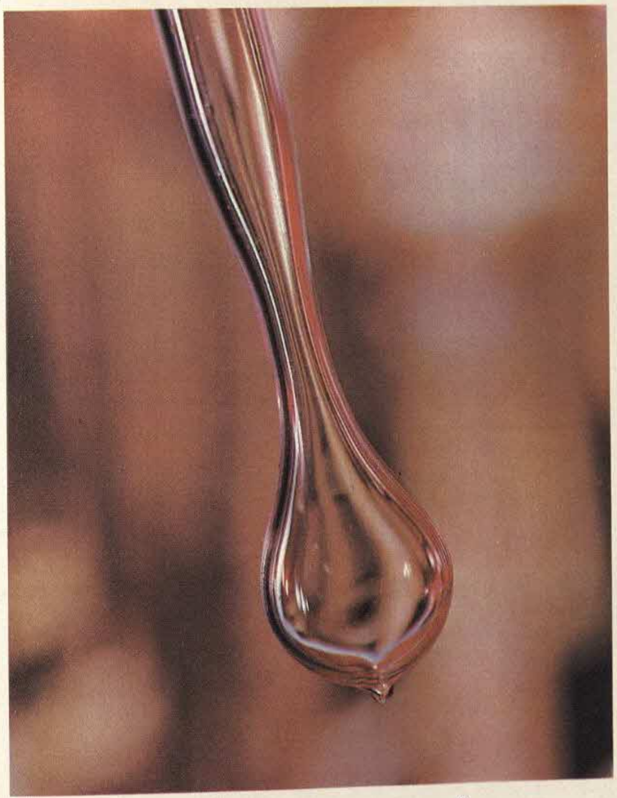


been defrauded by his goldsmith.

The point is that both objects were totally immersed in water and hence displaced an amount of water equal to their respective volumes. Both had the same weight, but the crown had a larger volume. Density is defined as the ratio of weight to volume; hence the crown had a smaller density—corresponding to the smaller density of a gold-silver alloy compared to the density of pure gold.

These facts are related to a principle—

c

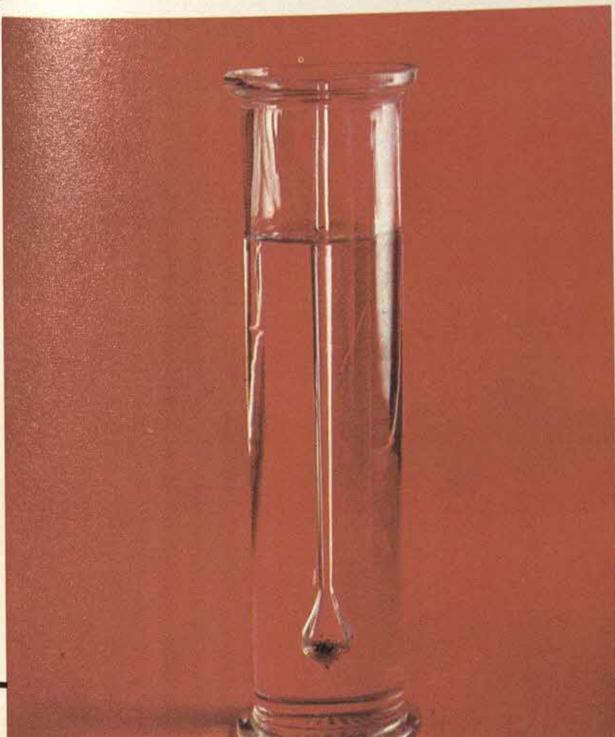


diameters of capillary tube.

The bulb is then filled with small lead shot, and an attempt is made to immerse the instrument in the least dense of the liquids that are to be tested for specific gravity (Illustration 1f). The shot is added only until the top of the capillary tube is just above the surface of the liquid. Then, two liquids, with the maximum and minimum densities for which the hydrometer is intended to be used, are prepared. A strip of paper is placed in the capillary tube to mark the levels of each of these liquids, defining the range of specific gravities to be measured. The space between these two marks is divided into equal intervals, and the paper is put back into the capillary tube in precisely the position it had during the initial marking of the minimum and maximum levels. The top of the capillary tube is then closed.

The hydrometer is now completed. Its accuracy will depend on how carefully the graduated scale was made, and especially on the use of liquids of known specific gravity for the two terminal markings defining the range of the scale. For example, water and alcohol may be used; for particular requirements two other liquids of known specific gravities may be used. Many practical hydrometers are made on this principle, but with the scale calibrated to show the specific gravities of mixtures, such as a mixture of alcohol and water. In such cases, the scale is not read in terms of the specific gravity but directly in terms of the percentage of alcohol in the mixture. Such a hydrometer is known as an alcoholometer.

f



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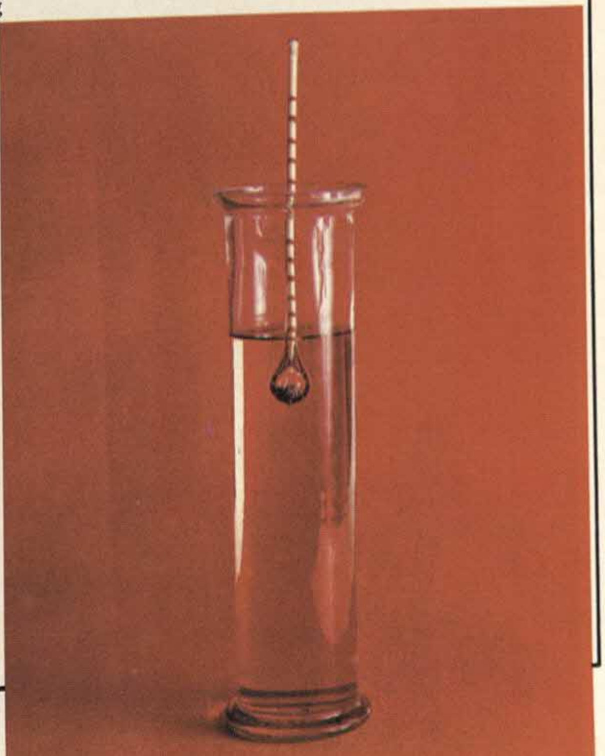

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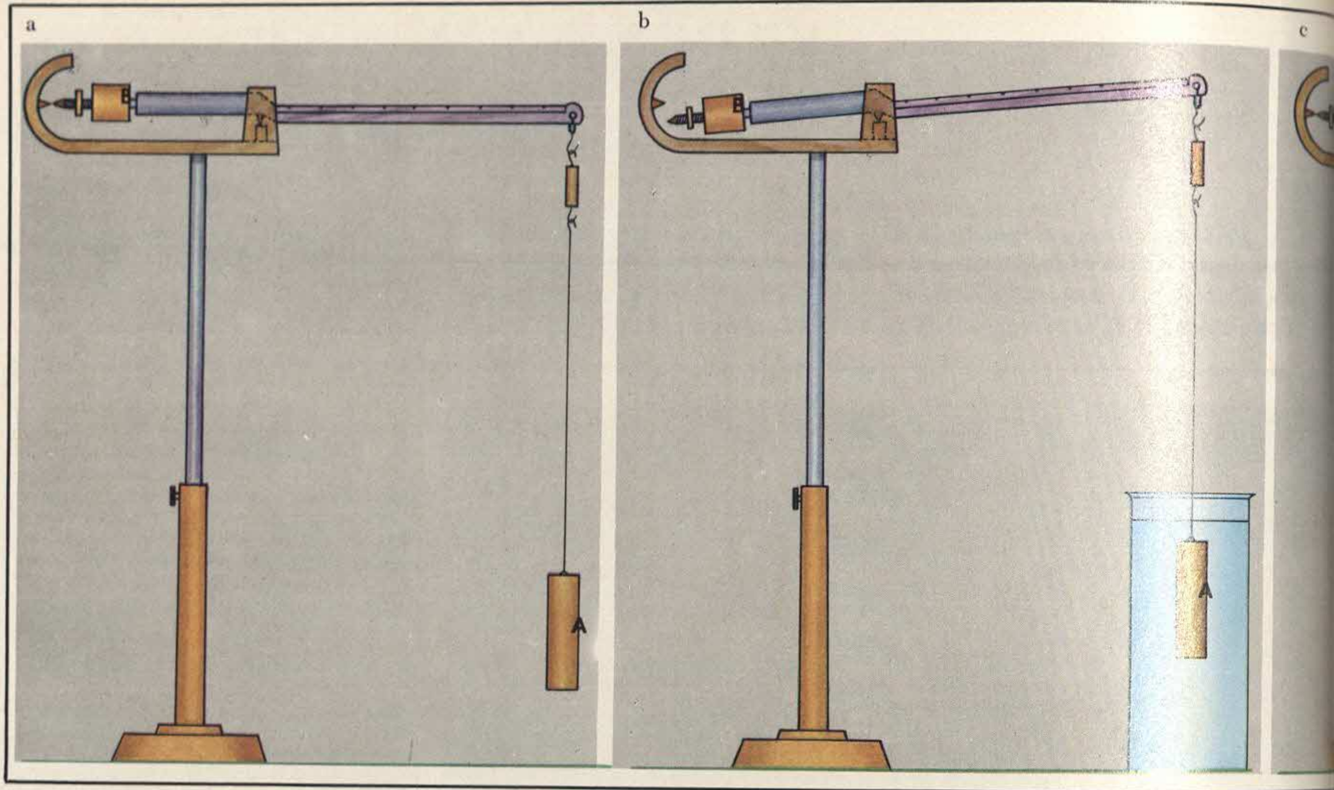
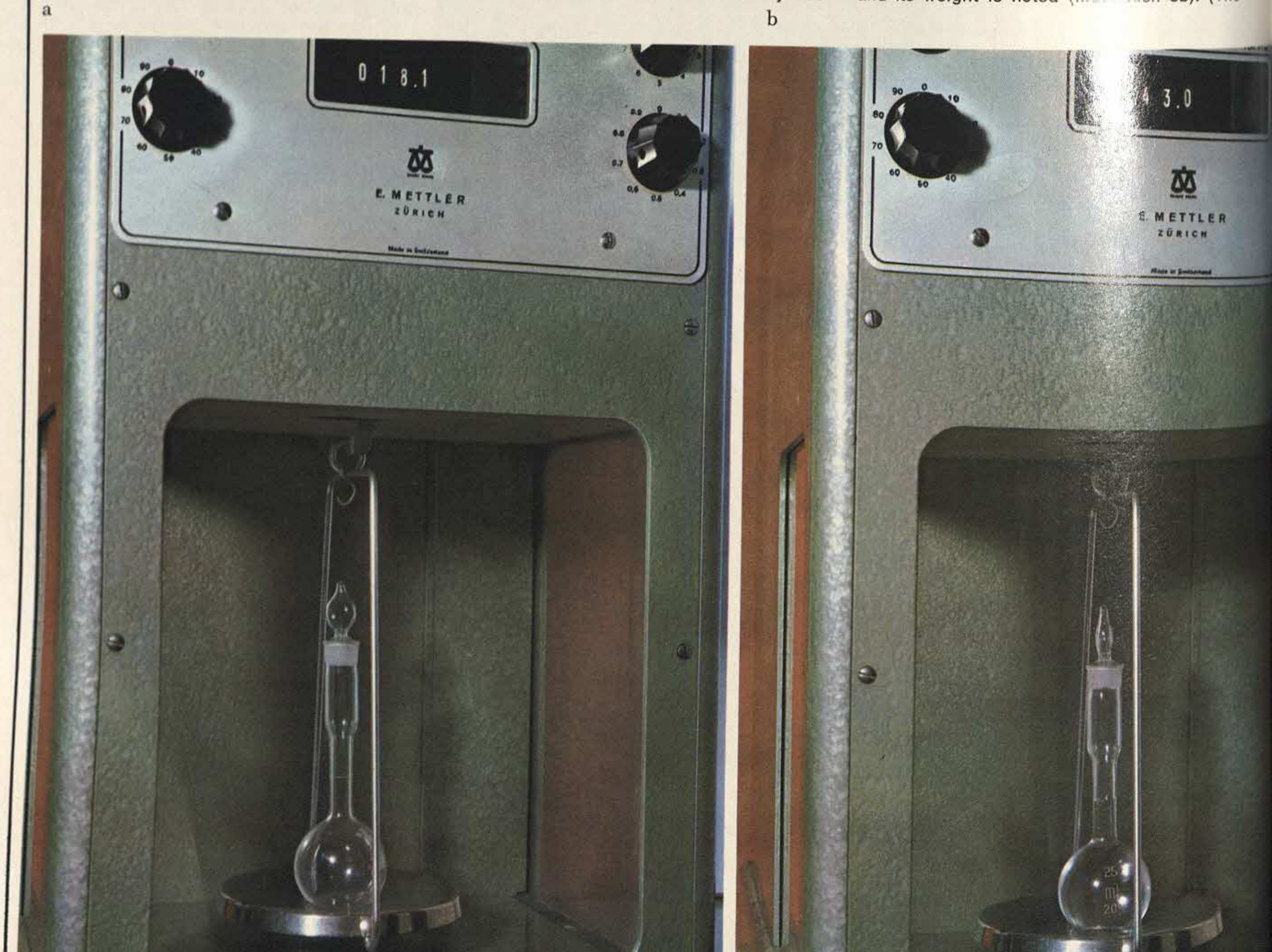
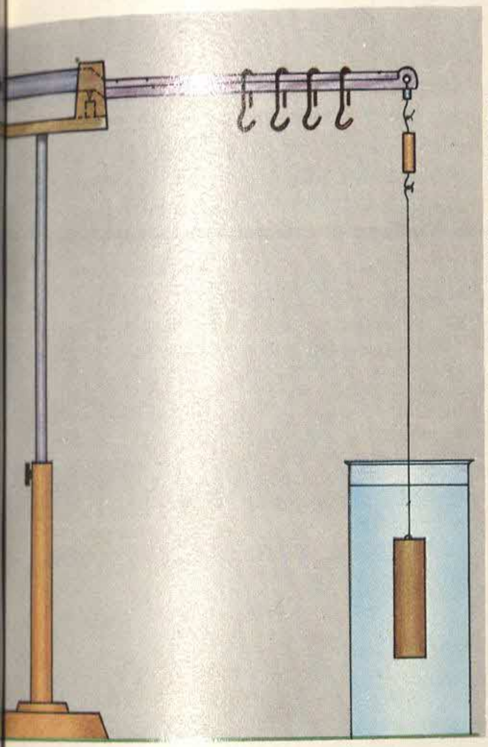


3

THE PYCNOMETER—A pycnometer is a specially constructed glass container used to measure the specific gravity of liquids. The container is first weighed empty, and its weight is noted (Illustration 3a). The container is then filled with distilled water, and its weight is noted (Illustration 3b). (The weight of the specific volume of water alone is found by subtracting the weight of the container from the weight just noted.) The container is then filled with the liquid to be tested for specific gravity, and its weight is noted (Illustration 3b). (The





THE MOHR-WESTPHAL BALANCE FOR LIQUIDS—The Mohr-Westphal balance can be used to determine the specific gravity of liquids as well as that of solids.

In Illustration 2a, an object of known density **A** is suspended from the long arm of the balance, and the equilibrium of the balance is attained by adjusting the threaded counterweight **B.** In Illustration 2b, the object is immersed in the liquid under test. The buoyancy of the liquid thrusts the object upward, ending the equilibrium of the balance. In Illustration 2c, riding weights are placed on the arm until equilibrium is regained; the total of these weights is the weight of the liquid displaced by the object.

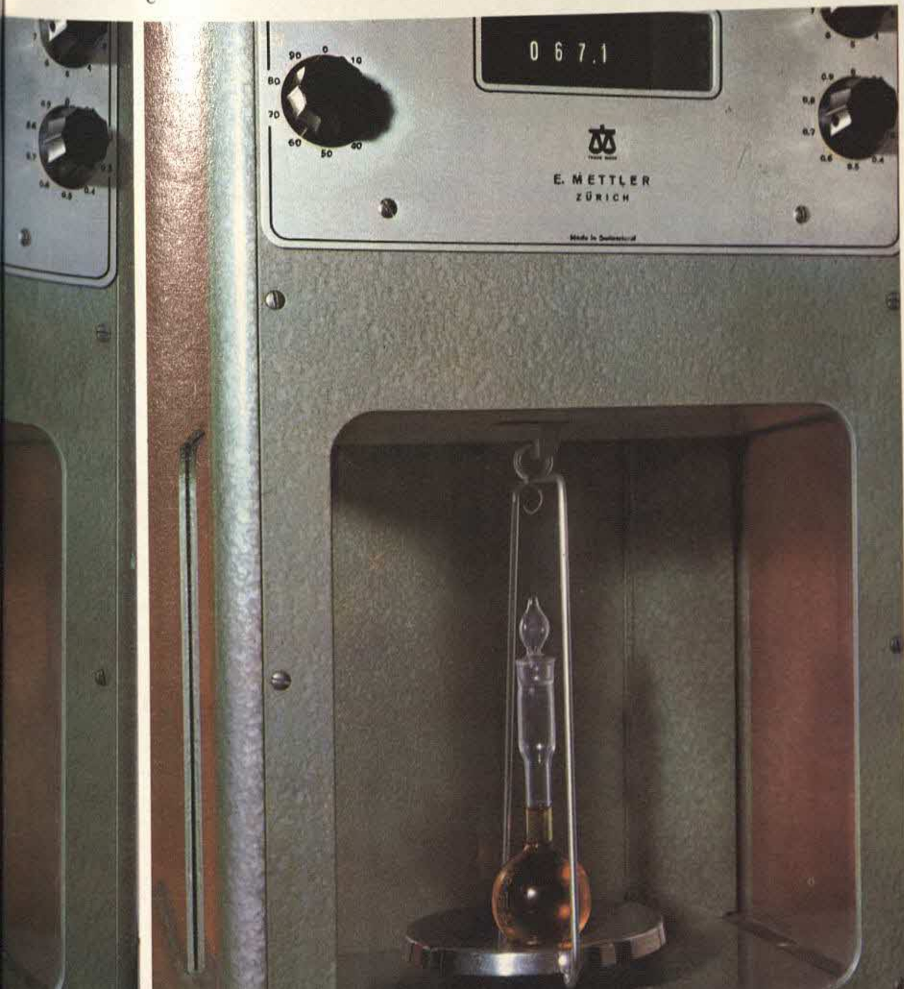
To find the specific gravity of the liquid, the weight of water displaced by the object (easily determined, because the density and volume of the object are known) is divided by the weight of the liquid determined in this operation.

The balance is accurate enough to record variations in the specific gravity of the same liquid caused by temperature changes. This can be done either by immersing a thermometer in the liquid during the operation or by using a weighted thermometer as the object of known density to be immersed.

weight of the same volume of this liquid alone is found by subtracting the weight of the container from the weight just noted.)

The specific gravity of the liquid under test is found by dividing the weight of the liquid alone by the weight of the water alone.

c



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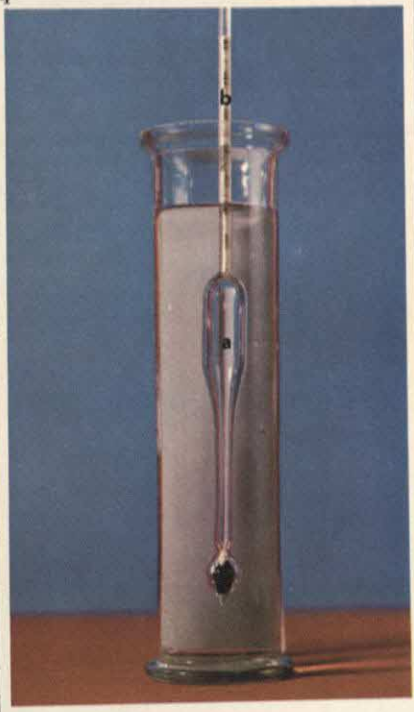


THE HYDROMETER—A rapid measurement of the specific gravity of a liquid is obtained by using a hydrometer (a kind of densimeter). This consists of a specially constructed glass container weighted at the end with lead shot or mercury. The container is somewhat rounded and bulb-shaped in its lower part **a** above the tube connecting with the weighted tip; the upper part **b** is a thin tube or capillary. The specific gravity of the entire hydrometer is less than that of the liquid to be tested; when placed in this liquid, it sinks until it has displaced a volume of the liquid with a weight equal to the hydrometer itself. (Another way of stating Archimedes' principle, known as the law of buoyancy, is: A floating body displaces its own weight of the liquid in which it floats.) If the specific gravity of the hydrometer is only slightly less than that of the liquid, and the capillary is very long and thin, extremely minute variations in the density of the liquid will cause perceptible variations in the depth of immersion.

The capillary tube is calibrated in such a way that the lowest mark on the scale corresponds to the specific gravity of the densest liquid that can be measured, and the highest mark corresponds to the specific gravity of the least dense liquid, with intermediate readings for liquids of intermediate density. Once the hydrometer is immersed and becomes stable, reaching its proper depth, it is possible to read the specific gravity of the liquid from the scale where it meets the surface of the liquid. The larger the bulb and the thinner the capillary, the more accurate the readings, but the range of specific gravities that can be read becomes narrower. In any case, the degree of accuracy of a hydrometer depends less on the capacity of the user than on the care with which the instrument was made, whereas the skill of the user is of primary importance in the case of the Mohr-Westphal balance and the pycnometer.

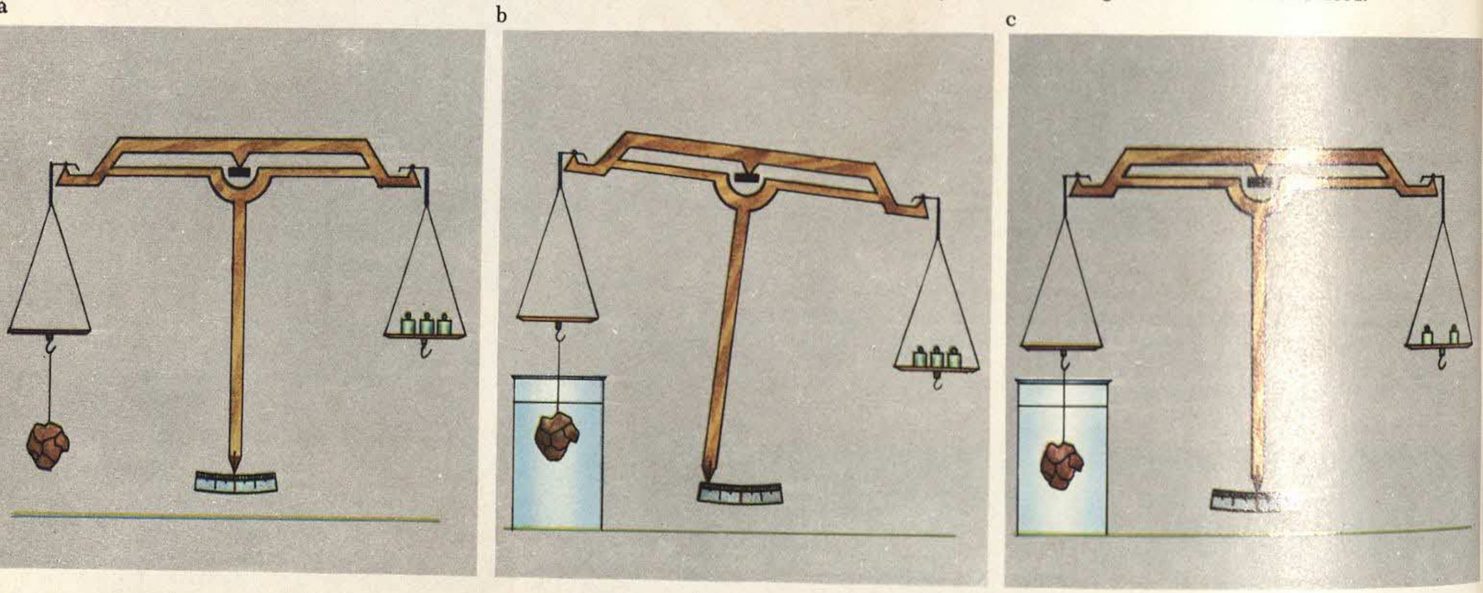
known as Archimedes' principle—stating that a body will weigh less in water than in air by an amount exactly equal to the weight of water displaced. If the body is totally immersed, then the displaced water will correspond to the volume of the object. If the body is floating, the weight of the displaced water will equal the weight of the object. Either of these approaches may be used to determine the density of various objects. The ratio between the density of an object and that of water is known as the specific gravity of the object. A number of devices, based on Archimedes' principle, may be used to determine the specific gravity of both solid and liquid objects, including the hydrostatic balance.

5

THE HYDROSTATIC BALANCE—The functioning of a hydrostatic balance is based on the simple principle that the equilibrium of the balance is maintained only if the weight on one side equals the weight on the other side.

The object whose specific gravity is to be determined is attached to one side, and weights of known value are attached to the other side until the balance attains equilibrium (Illustration 5a), at which point the value of the weights is totaled and this total is noted as the weight in air of the object under test.

In Illustration 5b, the two sides remain the same as in the previous operation, the object under test suspended on the left and the weights on the right. A glass of water is placed under the object so that the object is immersed. The force of buoyancy—an upward-thrusting force opposite to that of gravity—ends the equilibrium of the balance. This equilibrium is restored by removing some of the weights (Illustration 5c). The total of the remaining weights is the weight of the object in water; the total of the weights removed is the weight of the water displaced by the object. To find the specific gravity of the object, the weight of the object in air is divided by the weight of the water displaced.



THE MOHR-WESTPHAL BALANCE FOR SOLIDS—The German chemists Karl F. Mohr and Wilhelm H. Westphal devised a hydrostatic balance that operates on the same principle as the balance in Illustration 5, but more efficiently. The balance is placed in equilibrium by allowing the long arm on the left to carry a specific number of rider weights that can be removed. When the object to be tested is attached, enough of these rider weights are removed to maintain the equilibrium; their total weight equals that of the object attached. When the object is immersed in water, thereby losing weight, enough riding weights are restored to the arm to regain equilibrium; their total weight is that of the water displaced. The specific gravity of the object is found by dividing the first total by the second.

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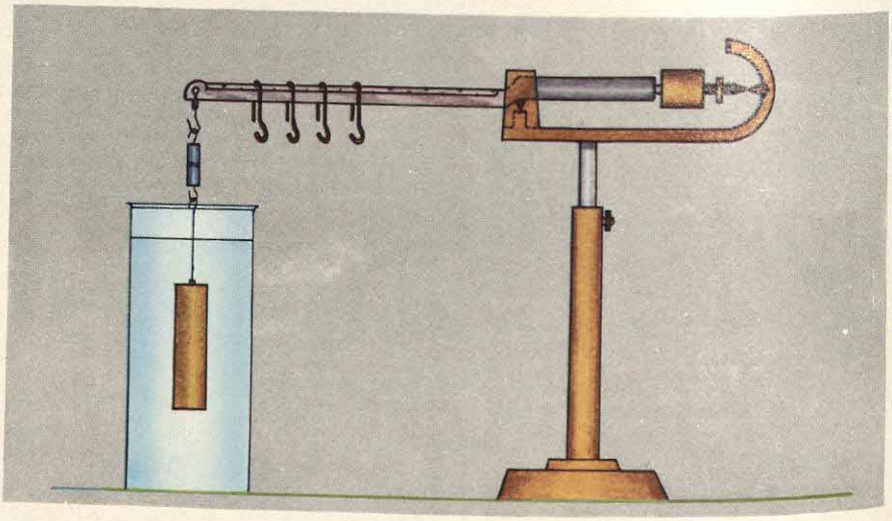

DILUTE SOLUTIONS

measurements of molecular weights

Dilute liquid solutions display a number of physical properties that do not depend on the kind of molecules in the solute (the dissolved matter), but rather on the number of those molecules. These properties are the lowering of vapor pressure, the raising of the boiling point, the lowering of the freezing point, and osmotic pressure, collectively sometimes designated as colligative properties.

If a certain quantity of a solute is placed in a solvent and no chemical reaction is involved, these colligative properties are apparent to a degree that is not in proportion to the quantity (in weight) of the solute used, but in proportion to the actual number of molecules or ions found in the solution, regardless of their weight or size. For example, a quarter grain of sodium chloride (salt) will produce a greater variation in the colligative properties in a given quantity of solvent than a quarter grain of copper iodide, merely because there are more molecules in a quarter grain of salt than in a quarter grain of copper iodide—that is, a molecule of salt weighs less than a molecule of copper iodide. Another way of expressing this last fact is by using the concept of the mole (the atomic weights of all the atoms in a molecule, expressed in grams): a solution is described as dilute or concentrated according to the lesser or greater number of moles (of a given solute) in, say, a liter of the solution.

LOWERING OF VAPOR PRESSURE

Vapor pressure is the tendency of a liquid to vaporize, or the amount of pressure required to restore a vapor to its liquid phase. If a solute with negligible vapor pressure is added to a solvent with considerable vapor pressure, it can be proved through experiment that the vapor pressure of the solvent will be lowered, in proportion to the concentration of the solute (that is, the number of moles it contains). This relationship was formulated by François Marie Raoult, a French chemist.

If P_0 represents the vapor pressure of a pure solvent and P the vapor pressure of a solution consisting of n_2 moles of solute and n_1 moles of solvent, then the amount of decrease in vapor pressure that occurs when the solute is added to the solvent is equal to the product of the vapor pressure of the solvent and the mole fraction of the solute (the ratio of moles of the solute to those of the solution):

$$P_0 - P = P_0 \frac{n_2}{n_1 + n_2};$$

and the vapor pressure of the solution is equal to the product of the vapor pressure of the pure solvent and the mole fraction of the solvent (the ratio of moles of the solvent to those of the solution):

$$P = P_0 \frac{n_1}{n_1 + n_2}.$$

These equations lead to the following usual expression of Raoult's law: The relative lowering of the vapor pressure is equal to the mole fraction of the solute:

$$\frac{P_0 - P}{P_0} = \frac{n_2}{n_1 + n_2} = \frac{n_2}{N}.$$

If the solute is ionized, the number of moles in the solute n_2 must be multiplied by a whole number corresponding to the number of ions produced by a molecule of the solute—for example, 2 for sodium chloride. Inasmuch as the lowering of the vapor pressure is proportional to the number of particles in solution, the ionization will cause the vapor pressure, in the case of a sodium chloride solute, to double.

The molecular weight of the solute can easily be calculated by measuring the vapor pressure of the solution. The number of moles of a substance n equals the ratio between the weight of the substance in grams g and its molecular weight M:

$$n = \frac{g}{M}.$$

Understanding that M_1 is the molecular weight of the solvent, M_2 is the molecular weight of the solute, and G is the weight of the solvent in grams, and substituting these values for n in a previous equation,

$$\frac{P_0 - P}{P_0} = \frac{\frac{g}{M_2}}{\frac{G}{M_1} \times \frac{g}{M_2}}.$$

In the case of dilute solutions, the term n_2 or $\frac{g}{M_2}$ in the denominator can be neglected, since it is much smaller than n_1:

$$\frac{P_0 - P}{P} = \frac{\frac{g}{M_2}}{\frac{G}{M_1}} \text{ or } \frac{g}{M_2} \times \frac{M_1}{G}.$$

If the weight of the solute added to the solvent and the molecular weight of the solvent are known, this equation will give the molecular weight of the solute by measuring the vapor pressures of the solvent and the solution. However, inasmuch as the vapor pressure is greatly dependent on the temperature, difficulties are encountered in making accurate measurements, and this method is not in general use.

CRYOSCOPY AND EBULLIOSCOPY

It is possible to determine the molecular weights of solutes and the concentration and osmotic pressures of solutions by determining the freezing points and boiling points produced in solvents by the addi-

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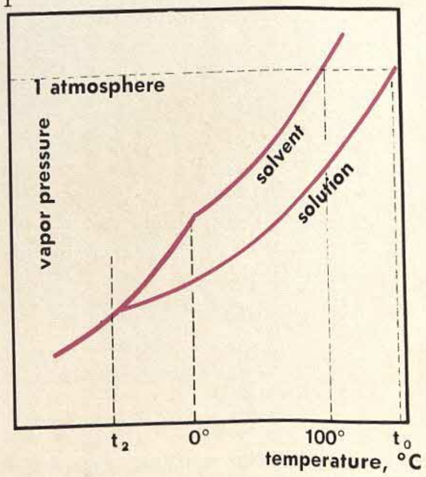


RAISING THE BOILING POINT AND LOWERING THE FREEZING POINT—If a nonvolatile solute is added to a solvent, the resulting solution will have a higher boiling point and a lower freezing point than the pure solvent. In this graph, the ordinate represents vapor tension and the abscissa represents temperature; the solute is sodium chloride (salt) and the solvent is water. According to Raoult's law, the curve for the solution will be lower than that of the solvent. Therefore, the curve intersects the line representing a pressure of 1 atmosphere (760 mm or 29.92 in. of mercury) at a temperature exceeding 100° C (t_0); this intersection point represents the boiling point of the solution. By analogy, the freezing point will be less than 0° C, and is represented on the graph at t_2.

tion of solutes. This process is known respectively as cryoscopy (in the case of freezing points) and ebullioscopy (in the case of boiling points).

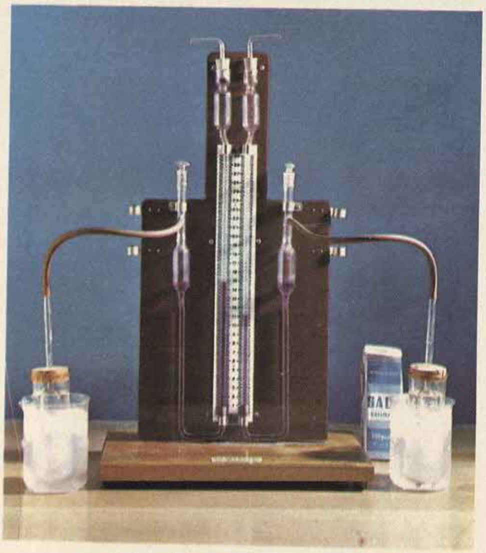
Because the presence of a nonvolatile solute—one with negligible vapor pressure—influences the vapor pressure of the solution, it must also affect the boiling point of the solvent; for the boiling point is in fact that point at which vapor pressure becomes equal to atmospheric pressure. If the presence of a solute in a solvent causes a decrease in vapor pressure, it must thereby cause a corresponding increase in the temperature at which the solvent will boil. Similarly, if a solution, because of the presence of a solute, has a lower vapor pressure than the pure solvent, it will freeze at a lower temperature.

The lowering of the vapor pressure is proportional to the concentration of the solution; it, therefore, follows that this will apply to these new factors, with the distinction, however, that the concentration will be expressed not in terms of mole fractions (as before) but in terms of molal fractions. (Mole fractions refer to volume—1 mole of solute to 1,000 milliliters of solvent; whereas molal fractions refer to weight—1 mole of solute to 1,000 grams or 1 kilogram of solvent.)

The symbol Δt is used to represent either the lowering of the freezing point or the raising of the boiling point; this value will increase in proportion to the quantity of the solute. When 1 mole of a specific substance (a solute) is dissolved in 1 kg of solvent, it lowers the freezing point or raises the boiling point by a value that is known as the cryoscopic or ebullioscopic constant for that substance, and is represented by K. The molal concentration—the number of moles per kg of solvent—is represented by c. By multiplying these two factors, the cryoscopic (or ebullioscopic) constant and the molal concentration, the value of Δt is obtained; that is, $\Delta t = Kc$. Now, if P grams of solute are dissolved in 1 kg of solvent, and PM is the molecular weight of the solute, then a proportion is established: $P : \Delta t = PM : K$.

CRYOSCOPY—The apparatus shown in the photograph, known as a double thermoscope, is used to verify the fact that a solution (in this case, brine) has a lower freezing point than the pure solvent (water).

2



OSMOTIC PRESSURE—If two solutions of identical composition but different concentration are separated by a semipermeable membrane (Illustration 3a)—one that permits only the solvent to pass through it—the direction of flow will be from the more dilute to the more concentrated solution (left to right in the illustration). This flow will continue until the hydrostatic pressure resulting from the difference in level between the two solutions is exactly balanced by the osmotic pressure exerted by the solute (Illustration 3b).

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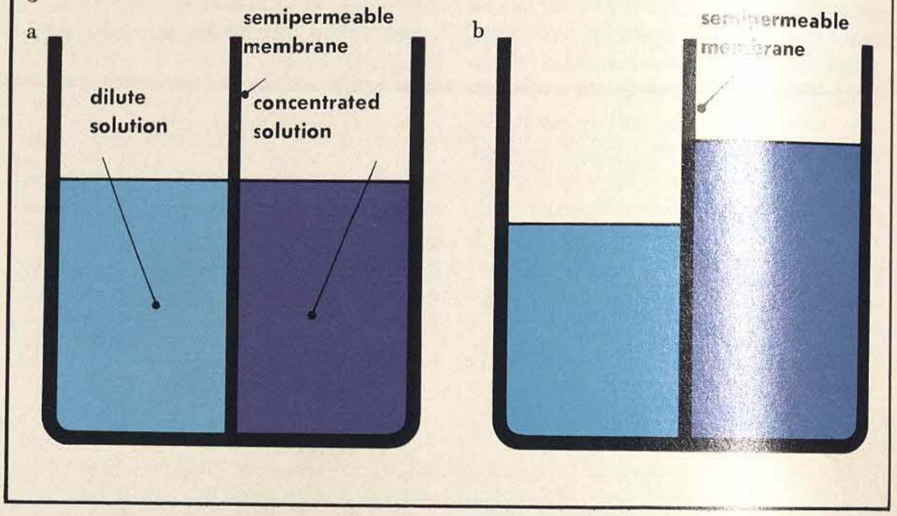

Using a solute of known molecular weight PM, the value of K (which is constant for any given solvent) can be calculated thus:

$$K = \frac{PM \times \Delta t}{P};$$

and the same experiment can be carried out with solutes of unknown molecular weight. In fact, from the preceding equation it follows that $PM = PK/\Delta t$, indicating how this unknown quantity can be calculated.

These methods for the determination of molecular weight give more reliable results because they can readily be put into practice. The variation of temperature can be very accurately measured with differential thermometers; slight variations of atmospheric temperature, moreover, will have no effect on the results. The cryoscopic method is preferable to the ebullioscopic method, because ebullioscopic constants are smaller than cryoscopic constants and would, therefore, require exceedingly accurate measurements.

All the methods described—the determination of vapor pressure, cryoscopy and ebullioscopy—produce valid results only when dilute solutions are involved; when concentrated solutions are used, molecular weights will be obtained that will differ from those obtained by other means, because as a solution becomes more concentrated interaction increases between the ions. Instead of complete dissociation, merely an equilibrium occurs between the dissociated and undissociated molecules.

Another phenomenon that frequently occurs and that must be avoided consists of the association of the undissociated molecules of the solute. This occurs, for example, when labile or changeable bonds are established between one molecule and another—hydrogen bonds are a case in point—or when polar molecules interact.

Aside from the interaction between the particles of the solute, another considerable source of error may be the interaction of the molecules of the solute with those of the solvent, as in the formation of compounds. In such cases, the solvent is no longer merely a solvent but is chemically active, and this activity influences the results.

The principle of cryoscopic lowering has practical applications. For example, salt is often spread on icy streets in winter to lower the freezing point of the water and to melt the ice or prevent further icing. The antifreeze used in automobile radiators is another example; it may have an ethylene glycol base with other additives, capable of considerably lowering the freezing point of water.

OSMOTIC PRESSURE

Dilute solutions of liquids resemble gases in many ways:

1. In both cases, the actual volume of the molecule is very small in comparison with the space occupied.
2. When a certain quantity of a gas is placed in an empty container, the gas molecules will diffuse throughout the container so that the concentration of the gas will be the same throughout the space; similarly, when a salt is dissolved in water, it will diffuse uniformly throughout the solvent.
3. The molecules of a gas in a container exert pressure against the walls of the container; similarly, solutions exert a special kind of pressure, known as osmotic pressure. For example, a few drops of blood added to water will redden the water because the water can permeate the cellular membrane and enter the cells; these swell, increase in size until they burst, and release the cellular fluid, which diffuses uniformly throughout the solution and colors it. However, if the same quantity of blood were to be placed in a solution that had higher concentration than the cellular solution, the cells would shrivel and the solution would not be colored. This phenomenon can be demonstrated experimentally by using semipermeable membranes that will retain the solute but will allow the solvent to pass. Such membranes are quite common in both plant and animal life.

Thus, if two solutions are prepared, identical in composition except for the degree of concentration, and separated by a semipermeable membrane, the solvent will pass through the membrane from the less concentrated to the more concentrated solution until the concentration on both sides of the membrane is the same. The level of the two solutions, which will have been the same at the start of the experiment, will be different once equilibrium in concentration has been achieved—it will be higher on the side of the membrane occupied originally by the more concentrated solvent. The molecules of the solute exert a pressure on the membrane and this causes the flow of the solvent across the "wall" between the two solutions. Equilibrium is attained when the hydrostatic pressure resulting from the difference in level between the two solutions is equal to the osmotic pressure of the solute.

This flow of a solvent from a dilute to a more concentrated solution is known as osmosis, and the pressure required to prevent such a flow is known as osmotic pressure. Two solutions exerting the same osmotic pressure are said to be isotonic; solutions will be isotonic only if equal volumes contain an equal number of molecules of the solute.

The Dutch physical chemist J. H. van't Hoff observed that the laws governing the behavior of gases are analogous to those affecting osmotic pressure. He formulated a principle, known as Van't Hoff's law, which states that a solute exerts as much osmotic pressure, when dissolved in a solvent, as it would exert if it were gasified at the same temperature and occupying the same volume as that occupied by the solution. In other words, the numerical values of the osmotic pressure and the gaseous pressure would be identical if identical volumes of the gas and the solution contain an identical number of molecules. Thus, with π representing osmotic pressure, V the volume of the solution, g the weight in grams of the solute dissolved in V, PM the molecular weight of the solute, T the absolute temperature, and R a constant with the same value as that of gases,

$$\pi \times V = \frac{g}{PM} \times RT.$$

This equation can be used, just as in the case of gases, to calculate the molecular weight of an unknown substance, by transposing the terms thus:

$$PM = \frac{g}{\pi \times V} \times RT.$$

To use this formula, dissolve a known weight of the substance in a particular solvent; measure the volume, the osmotic pressure, and the temperature of the solution. Because R is a known constant, the molecular weight can be calculated.

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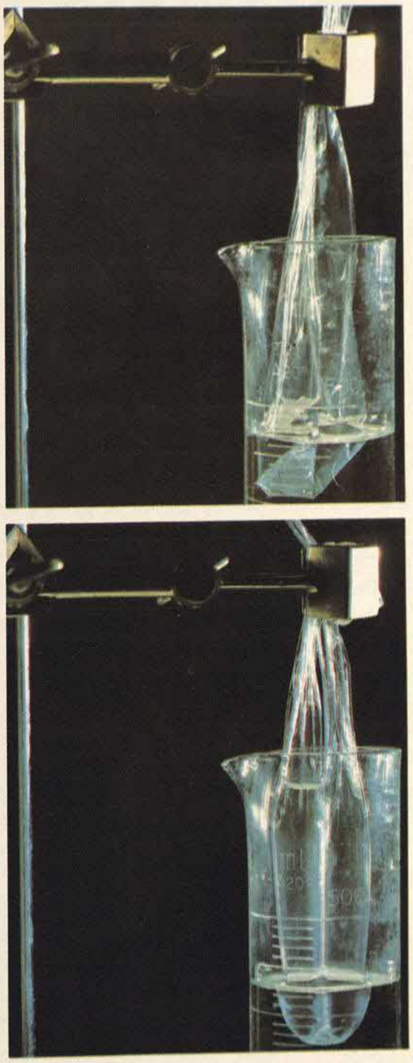

OSMOSIS—Illustration 4a shows a glass container holding a dilute solution. Suspended in the solution is a semipermeable bag holding a concentrated solution identical in composition to the contents of the glass. The solvent in the dilute solution penetrates the bag, although the solute does not. After some time the bag has become swollen with the extra quantity of the solvent (Illustration 4b) and the level of the solution in the glass has fallen, as shown by the calibration. This phenomenon is called osmosis; the pressure required to prevent the flow of the solvent from the less to the more concentrated solution is called osmotic pressure.

The laws, just as in the case of gases, are limited and apply only to dilute solutions; if applied to concentrated solutions, correction factors must be introduced. This method is useful to determine the molecular weights of substances with a high molecular weight.

COLLOIDS | microparticles dispersed in media

If a small amount of salt is placed in water and stirred, it forms a solution that has a salty taste but looks just like the water before the salt was added. If the water with salt dissolved in it is examined a little more thoroughly, however, it will be found to be somewhat denser than pure water; moreover, the salt can be extracted from it in several ways, one of which is by merely allowing the water to evaporate.

Now, if some ordinary gelatin, such as isinglass, is placed in water and vigorously stirred, it not only remains visible but increases in volume, swelling in a few hours to a volume several times greater than that of the original gelatin.

Careful study will show that the two mixtures of water and solid substance behave in completely different ways. For example, a container divided into two halves by the insertion of a permeable membrane, such as parchment, can be filled with pure water on one side and salt solution on the other side; the salt solution will diffuse through the membrane. However, if the second side is filled with the gelatin-and-water mixture, no such diffusion will occur.

Both mixtures contain particles that move about in the water, but the particles in the salt solution are small enough to pass through the microscopic holes in the membrane, whereas the gelatin particles are too large to do so—in some cases they are several hundred times as large as the salt particles dissolved in water.

A mixture of two substances composed of particles of small dimensions, say, less than 0.1 μm (micron), is called a colloid. A colloid behaves like the gelatin swollen in water; the smaller the dispersed particles in the colloid, the more pronounced are its characteristic properties. If the particles are very small, however, only slightly larger than atoms, the properties of the suspension are gradually transformed from those of colloids to those of true solutions, such as that of salt in water.

RUBY GLASS—Colloids that consist of solid particles dispersed within another solid are called solid sols. Venetian ruby glass is a solid sol, formed by dispersing particles of gold in the mass of glass. The gold particles of this colloid have a diameter of the order of 0.01 μm.

1

THE OBSERVATION AND STUDY OF COLLOIDAL PARTICLES

Colloidal particles are too small to be seen by the eye or even through an optical microscope; the largest colloidal particles have a diameter of about 0.1 μm, about one-third the size of the smallest object directly visible through an optical microscope. It is possible, however, by using a technique known as dark-field illumination, to "see" colloidal particles through a microscope of high magnification. The container in which the colloid has been placed is placed under the objective of the microscope; a beam of light illuminates from one side the area containing the particles to be viewed, in such a way that the particles scatter the light. It is the scattered light, of course, rather than the particles, that is seen. This operation is analogous to the illumination of dust particles suspended in the air by a ray of sunlight; particles that are otherwise not visible to the eye appear as tiny, luminous dots.

Colloidal particles dispersed in gases or liquids can also be observed by means of electron microscopes, which obtain great magnification and fineness of detail of objects far smaller than 0.1 μm. Not only can the particles themselves be observed; their dimensions can be measured and their forms can be observed, and sometimes they appear to be rather complicated. However, the technique for obtaining a good preparation for examination under an electron microscope is rather complex.

APPLICATIONS

The study of colloids is of great scientific and industrial importance; many processes involving animals and plants, and some even involving minerals, are studied by means of colloid chemistry. Colloidal grains account for the sensitization of photographic plates; the clay-

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PUMICE—Another kind of colloid consists of gas dispersed in a solid. Pumice is a form of lava, erupted from volcanoes, that solidified so rapidly that within it are trapped large quantities of volcanic gas as minute bubbles, some of which are fairly large but most of which are small enough to justify the classification of this rock as a colloid. Pumice is sometimes called volcanic glass, sometimes solid foam. Because it contains so much gas, pumice is often light enough to be buoyant, and floats on water.

maturing processes in the ceramic industry and the setting phenomena of cements are colloidal. Brewing, dyeing, tanning, the manufacture of rubber and soap, the purification of water—all involve problems in the field of colloid chemistry. This field is the basis for the massive industrial exploitation of synthetic fibers; their manufacture, particularly for use in textiles, is often made possible by chemical treatments that transform the raw colloidal product into a mass that can be drawn and reduced into yarn.

One extremely important field concerned with colloids is medicine, especially biochemistry, because much of the human body is composed of colloidal substances, including the tissues and even blood. Colloid chemistry, therefore, assumes great importance in the study of many serious illnesses that lead to the degeneration of these parts of the organism.

PROTECTIVE COLLOIDS

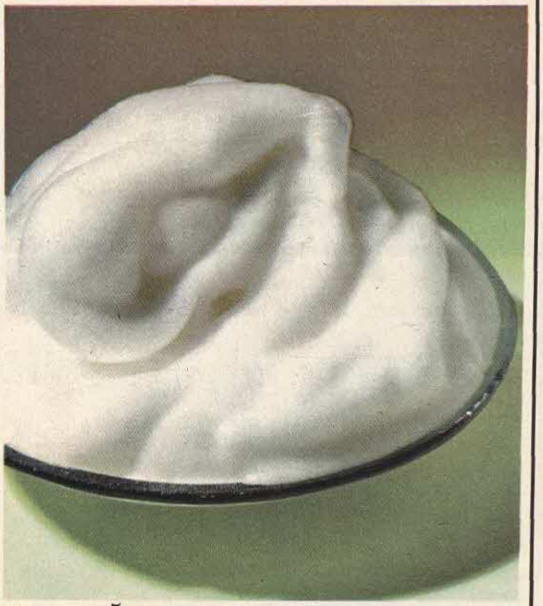
Some substances in the colloidal state are quite difficult to preserve, but can be made more stable by the addition of other colloids, usually organic substances, that are known as protectors. Silver bromide, for example, can be preserved in the colloidal state by adding 1 percent of gelatin, which acts as a protector. The measure of the protective effect of one colloid on another is known as the gold number. This represents the number of milligrams of a protector needed to prevent 10 cc of a gold hydrosol (a colloidal dispersion of gold particles in water) from turning from red to violet when 1 cc of a 10-percent solution of sodium chloride (salt) is added; the smaller the gold number, the greater the protective action of the colloid.

EMULSIFIED OIL—The suspension of microparticles of a liquid in another liquid constitutes a colloid known as an emulsion. The emulsion illustrated is composed of oil dispersed in water, and is used as a lubricant in metal-cutting operations carried out with machine tools. Its high water content enables it to cool the pieces of metal that are being worked.

GRAPHITIZED OIL—Solid particles suspended in a liquid medium as a colloid are called hydrosols; hydrosols are common in both organic and inorganic substances. This suspension of minute particles of graphite in water and oil is used as a lubricant for mechanical parts.

3

4



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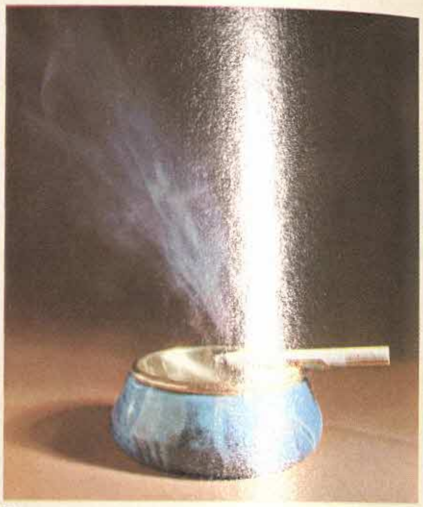
FOAM—This colloid consists of gases dispersed as bubbles within a liquid. Such a light, frothy mass formed in a liquid is known as a liquid colloidal foam.

6

SPRAY—The dispersion of colloidal particles of liquid in a gas is known as an aerosol. Such droplets may be as large as a micron in diameter and fall rapidly, while others are much smaller and remain suspended in air for long periods. Normal fog is such an aerosol.



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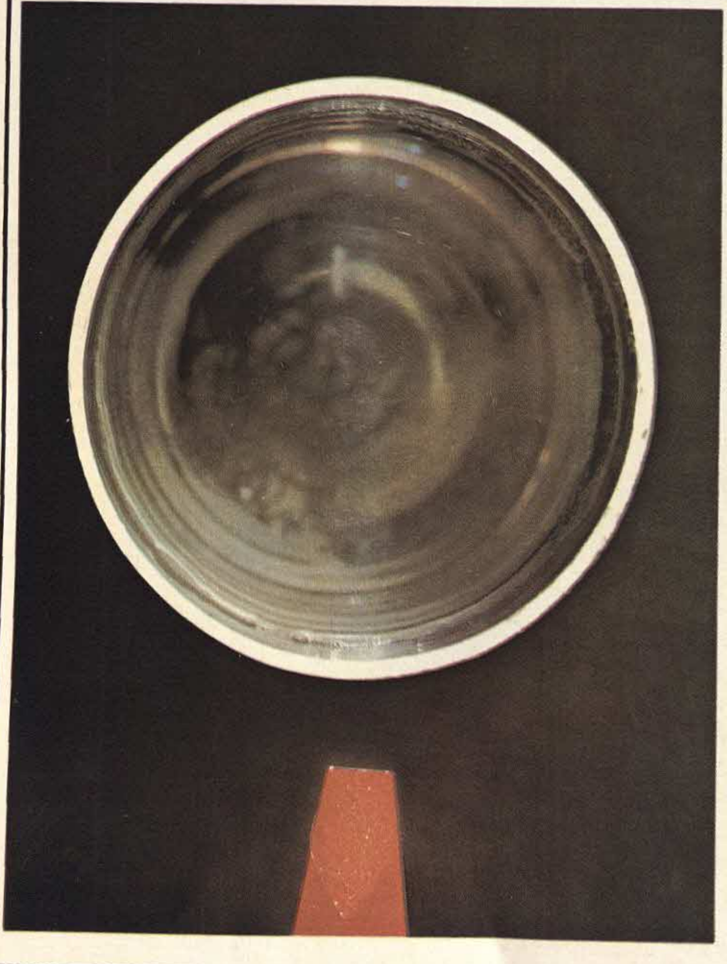
SMOKE—The dispersion of solid particles in a gas is called a solid aerosol. Examples are dusts projected into the atmosphere by volcanoes; dusts produced by the breakup of meteorites; dusts lifted from deserts by winds; smoke produced by incomplete combustion, sending particulate matter into the air to form smog. Cigarette smoke is another example of a solid aerosol.

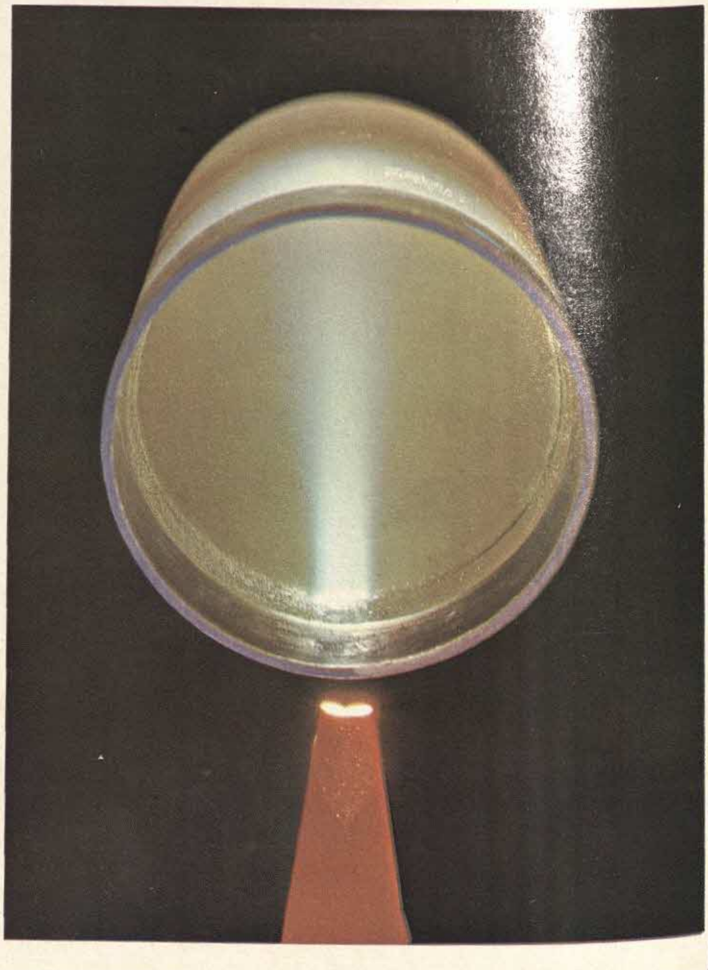
THE TYNDALL EFFECT—A ray of light passing through a homogeneous, transparent, and perfectly limpid substance cannot be seen. Illustration 8a shows a glass basin filled with pure water, through which a beam is thrown by a spotlight; the beam cannot be seen, although the walls of the basin reflect the light and show that the beam has passed through the water.

If a colloidal dispersion is produced in the water or in any other homogeneous substance, the minute particles of the colloid will diffuse the light in all directions. Illustration 8b shows a basin of water in which soap particles have been dispersed, forming a colloid; the path of the beam is clearly visible. This diffusion of light is called the Tyndall effect. It is commonly observed when a beam of light penetrates a dark room, illuminating the tiny and normally invisible dust particles in the air; the light appears as a beam.

8a



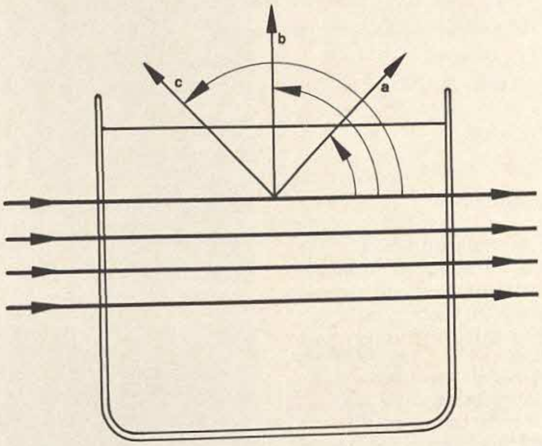
8b



LIGHT AND COLLOIDS | suspensions scatter light

The diffusion of light constitutes a very effective method for investigating some characteristics of colloidal suspensions. It can be verified by direct observation, for example, that suspensions of very large particles tend to scatter light away from its source, whereas suspensions containing minute particles tend to scatter light either in the direction of or at right angles to its source. Moreover, radiations with varying wavelengths are scattered in varying manners.

1



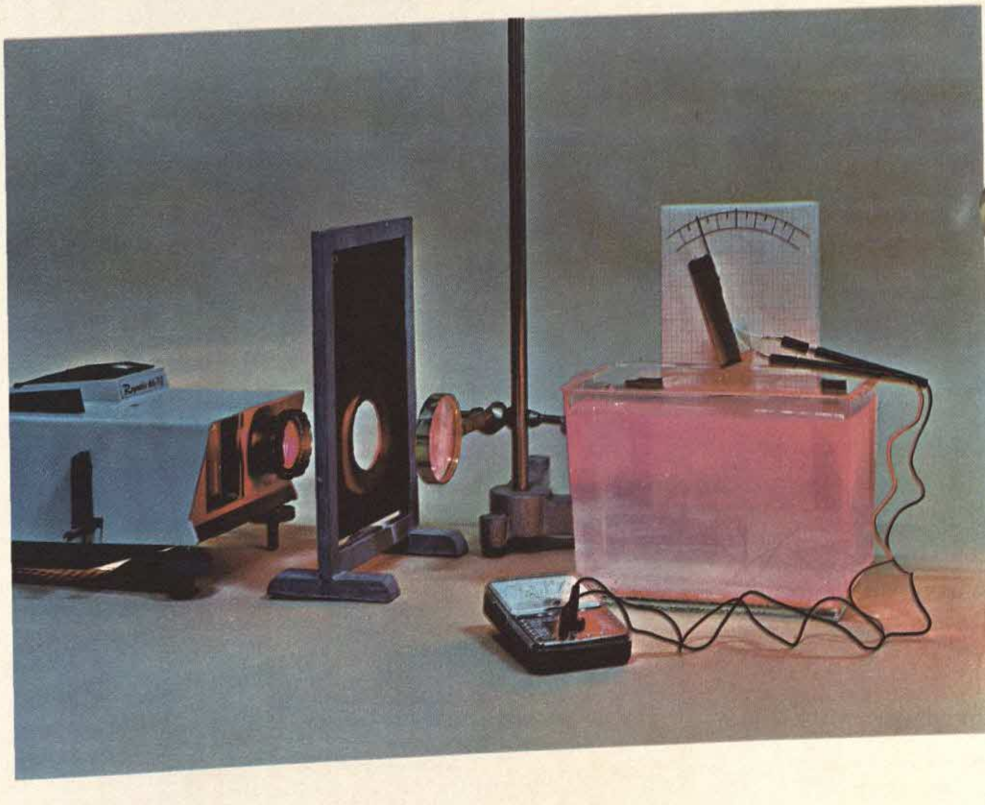
THE PRINCIPLE OF THE MEASUREMENT— This illustration shows the principle of the measurement. The colored glass or plastic container, transparent and fairly flat on at least one side, receives the suspension. A beam of white light is projected into the container. If the container were empty or filled with limpid water, the beam would pass through it without being visible; when the water contains suspended particles, however, luminosity of a certain intensity marks the path of the beam, because the particles scatter the light as it strikes them, reflecting this light in all directions. Thus, light can be observed that has left the direction of the original beam and follows the directions indicated by the arrows **a, b,** and **c.** When a photometer is placed so that its axis lies on one of these arrows, the experiment can be launched. First, if the light fails to reach the objective (lens system) of the photometer, zero illumination will be registered by what is called a current of darkness on the photometer; but if scattered light does reach the instrument, a deviation from the current of darkness occurs. This deviation makes it possible to measure the value of the illumination, depending on three factors.

The first factor is the intensity of the beam. The second is the concentration of the suspension: in a dilute suspension, only a few suspended particles will be present to diffuse the light, whereas in an excessively concentrated suspension, particles will absorb part of the light, leaving less to be scattered. The third factor is the angle at which the measurement is made, which will affect the intensity measured.

If the intensity of the beam and the density of the suspension remain constant, the intensity of the scattered light can be determined at any angle; different results will be obtained by measuring in the direction of **a, b,** or **c.** To measure the concentration of the suspension, a calibration would have to be devised by filling the container with various solutions of known concentration and measuring the different diffused intensities at each concentration. Once a calibration curve has been constructed in this manner, the value of an unknown density of concentration can be calculated by interpolation. The instrument used to measure concentration is known as a nephelometer.

The most important observation is that of the variation of intensity of light scattered in the various directions: whether the light is diffused mainly in the direction of **a** rather than in the direction of **b** or **c,** and so forth. If the diffusion is mainly forward, this indicates that the average particle in suspension is of the same order of dimension as the wavelength of the radiation; if the opposite reaction occurs, the average size is smaller than that of the wavelength.

2



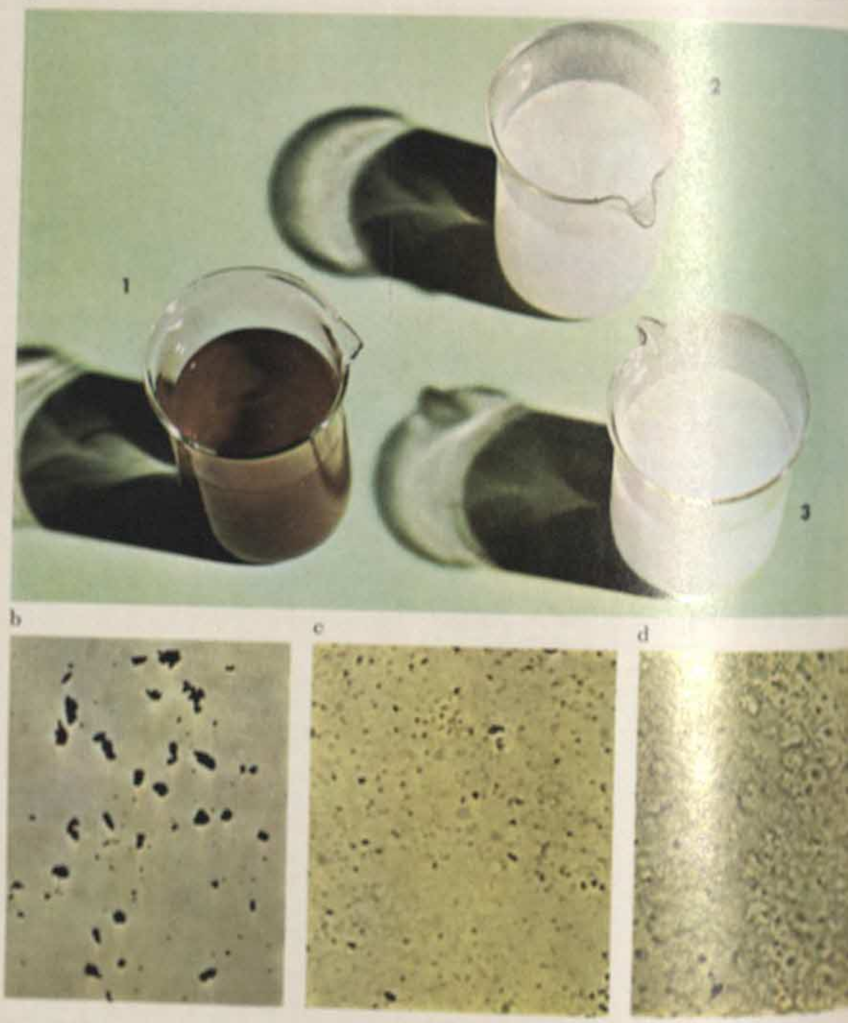
THE EXPERIMENTAL SETUP — This photograph illustrates the arrangement of the equipment needed to carry out the experiment. The source of the light is an ordinary slide projector of moderate power, arranged to throw its beam into a glass container with flat, parallel sides and containing an opaline liquid. A gelatin filter may be mounted on the objective of the projector, making a restricted range of wavelengths possible.

Measurements are made by using a photometer with a suitable type of detector mounted at the end of a wooden arm swiveling on a plywood board. The board is fixed to the side of the container as shown in the photograph, and on it is marked a protractor scale measuring the inclination of the wooden arm and, therefore, the angle at which the measurement is made.

The choice of the photometer, or more precisely of its sensitive element, is quite important; it must possess high sensitivity for the radiation and, if possible, for all radiations of the visible spectrum. An evacuated or, even better, gas-filled photoelectric cell is suitable for the purpose; but in the case of measurements with a red light, photodiodes or phototransistors can be used. If extreme sensitivity is not desired, a photoresistance can be used, particularly by virtue of the fact that it possesses a large area that is optically active and can, therefore, gather considerable diffused light.

Direct observation of particles in suspension, and particularly of their dimensions, is difficult and, without the use of an electron microscope, virtually impossible. However, an indirect determination of the dimensions of such particles can be made by the scattering of light, which in effect constitutes a comparison of the dimensions of the particles with the wavelengths of the radiation being used. The equipment required is fairly simple, the most important device being a photometer. A slide projector is needed to cast an intense light to be diffused by the colloid or the nonhomogeneous suspension. A container for the liquid with the suspension and some filters to select radiations of different wavelengths will also be necessary. Finally, a microscope is useful for observation of larger particles within the suspension.

3



PREPARING THE SUSPENSIONS—A number of suspensions may be prepared (illustration 3a) and tested before carrying out measurements of unknown suspensions.

A coarse suspension **1** can be prepared by putting a small quantity of fine iron oxide powder in water. In this and later instances, the density of the suspension must be such that for a thickness of 5 to 10 cm (about 2 to 4 in.) the suspension will be virtually transparent. Because of the size of the iron oxide grains, they will settle in a few minutes; the suspension must, therefore, be constantly agitated. Iron oxide is chosen because its particles are all more or less the same size.

A suspension of finer particles **2** can be obtained by putting a few drops of milk in a glass of water.

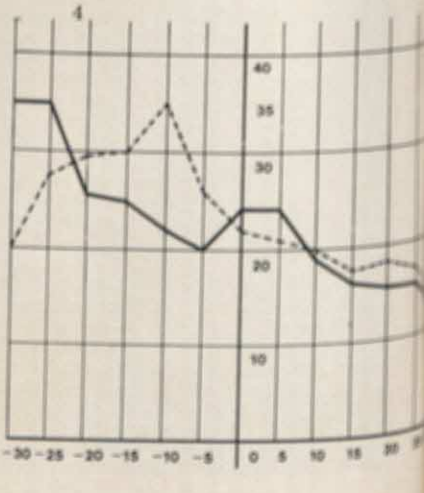
A colloid with extremely fine particles **3** can be obtained by putting some French polish (an oil-shellac mixture used for furniture) in water. The suspension shown here has an appearance similar to that of milk.

When examined under a microscope, the three suspensions **1**, **2**, and **3** are seen to have particles that differ greatly in dimension. The iron oxide (illustration 3b, 125 X) has grains that are quite visible, with distinct form and sizes that can be measured. The same can be said for the balls of milk fat (illustration 3c, 500 X). On the other hand, the other emulsion has no visible particles, because these are smaller than the wavelength of light and are beyond the power of the microscope to resolve; however, at 500 X (illustration 3d), they can be seen joined together in little balls.

THE MEASUREMENTS—*In order to examine the qualitative differences in the various kinds of colloidal dispersions, the two most significant of the three just described may be selected—the milk-and-water dispersion and the dispersion of water and shellac oil. In view of the empirical nature of the experiment, and in order to increase the sensitivity of the apparatus, a measuring method of the differential type is adopted. Beginning with red light, for example, the current is measured for the various angles registered on the protractor scale; after observing the various intensities of the current, the experiment is repeated with blue light. The differences in current intensity are then plotted as a graph. An identical procedure is followed for the second dispersion. Thus, two graphs will be obtained, and by plotting with different vertical scales they can be roughly superimposed.

In the graph of the shellac-oil dispersion, when the curve has passed—in respect to the direction of the origin of the beam—from an acute angle to an obtuse angle, it has a general downward slope. In the case of the milk dispersion, on the other hand, the curve shows maximum intensity of scattering, roughly perpendicular to the direction of the incident beam.

4



EMULSIONS | dispersions of liquids in liquids

Some liquids cannot be mixed with others. If oil is poured into a glass of water, it forms a layer on top of the water, but it will not mix with it. Because it is often desirable, for reasons of technology, to combine two liquids that are normally not miscible, special ways have been found to disperse one liquid in another, producing a type of colloid known as an emulsion. Whenever one liquid is dispersed in the form of quite small droplets within the mass of another liquid in which it is insoluble, an emulsion is formed; in this case, the liquid forming the small drops is called the dispersed phase, and the other liquid is called the dispersing phase.

A naturally formed emulsion is exemplified by milk, in which small fat particles are dispersed in an aqueous-sugary phase. Another is crude oil as it issues from a well; here various hydrocarbons are in an aqueous-salty phase. Emulsions are often characterized by a typical opalescence or milkiness. They may be obtained by beating two liquids for a period of time, but such an emulsion is not likely to last long.

The droplets of the dispersed liquid may vary in size, usually ranging between 1,000 and 30,000 Ångstroms. Such particles should not be confused with the large molecules typical of other colloidal substances; in an emulsion, each individual drop actually consists of thousands of simple molecules.

A major problem with emulsions is the separation of the component liquids. No rule applies generally; they can sometimes be separated by allowing sedimentation to take place over a period of time, or by forcing sedimentation through centrifugal motion. Both these methods are used to separate the fatty phase of milk (cream) from the aqueous-sugary phase. Other methods include the differentiation by temperature of the components and the addition of special substances.

EMULSIFIERS

As has been mentioned, unstable emulsions can be formed by merely beating the two component liquids; after a while, the two insoluble liquids tend to form separate layers, and the amount of the dispersed liquid is rather small.

The separation of the two phases is essentially based on thermodynamics. For an emulsion to be stable, the free energy of the emulsion must be less then that of the separated liquids ($\Delta G = \Delta H - T\Delta S$). Now, ΔS (the variation of the entropy) is positive in the mixing of the two liquids. The enthalpic term ΔH, however, is strongly positive—that is, work must be performed in order to create the emulsion, such as the beating of the two liquids—and the algebraic sum of the two terms is positive. After a while, therefore, the emulsion returns to the condition of minimum free energy; that is, it separates into two liquids.

It has been discovered that the presence of particular substances known as emulsifiers makes it possible to prepare emulsions that are stable for a long period of time and are fairly rich in dispersed liquid. Emulsifiers are usually classified as soaps or as fatty proteins (lipoproteins) such as the casein that stabilizes the fat component in milk.

The soaps are formed by an inorganic cation (positively charged ion), such as that of sodium or potassium, and an anion (negatively charged ion) with a lengthy chain, such as stearic acid, palmitic acid, lauric acid, oleic acid, and others. According to the most plausible theories, as in the case of emulsions of oil in water, the soaps act by becoming adsorbed to the interface between the droplets of dispersed oil and the dispersing aqueous phase; soaps thereby stabilize the droplets by causing a bond between the two liquids because the soap molecule has a partial affinity for the oily phase and also for the aqueous phase. The long soap molecules are said to be so arranged that the hydrocarbon part of the chain is in the oily phase and the end of the COO^-Na^+ ion is in the aqueous phase, thus binding the two phases. This theory is confirmed by the fact that other molecules, such as the alkyl-sulfonic acids, the quaternary ammonium salts, and the bile acids—all of which are hydrocarbon chains ending in ions—have the same emulsifying effects as do the soaps. It is also worth noting that the emulsifying capacity of a soap, at least up to a certain point, seems to be directly related to the length of the hydrocarbon chain—the longer the chain, the more active the soap. Beyond the limit of 18 to 20 carbon atoms, however, the fatty properties predominate and the soaps become insoluble in water. It should also be noted that the degreasing effect of the soaps depends on the formation of an emulsion of fats in water that is made possible only because of the presence of the soap.

An emulsion stabilized with soap can be separated into two liquid phases merely by adding some salt (sodium chloride). In this case the reaction is indirect, for the excess of salt actually separates out the soap, causing the emulsion to lose its emulsifying agent and therefore its stability, and resulting in the separation of the liquids into layers.

EMULSIFIERS AND WETTABILITY

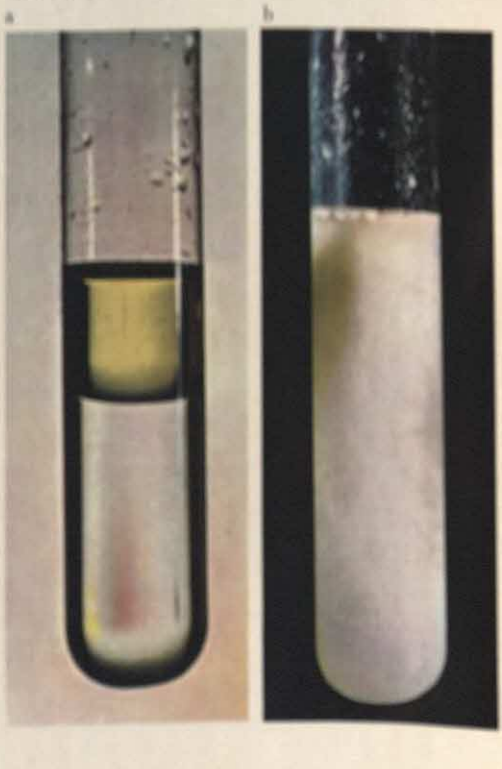
Just as it is possible to obtain an emulsion of oil (dispersed phase) in water (dispersing phase), so it is possible to obtain an emulsion of water (dispersed phase) in oil (dispersing phase).

It has also been found—although some aspects of the phenomenon are not too clear—that a relationship exists between the type of emulsion that an emulsifier

1

TWO LIQUIDS THAT DO NOT MIX—When two liquids that do not mix are combined, even when they are strongly agitated, no lasting emulsion forms because such a reaction is impossible for thermodynamic reasons: such a reaction would increase the free energy of the system, which is impossible. Instead, the two liquids will form layers more or less rapidly, until all the lighter liquid floats on the heavier liquid (Illustration 1a).

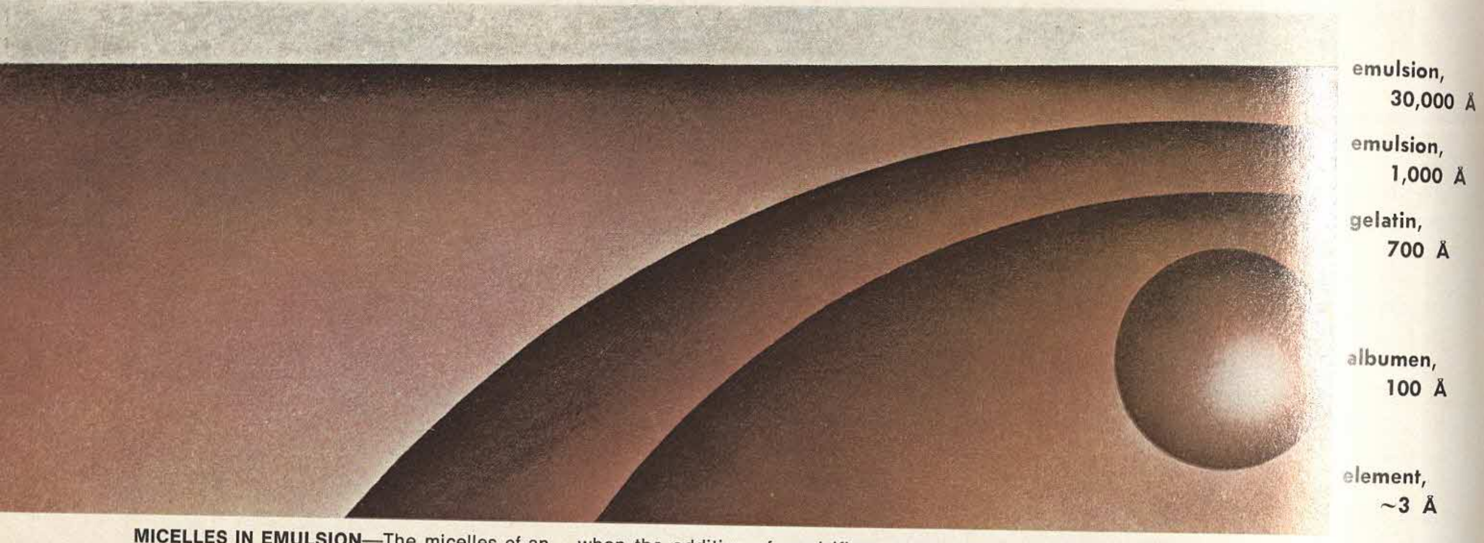
However, if a component is added to reduce the surface tension, the dispersed micelles are stabilized by a monomolecular film of the additive at the interface; the emulsion is stabilized, and the two liquids do not separate (Illustration 1b).



a

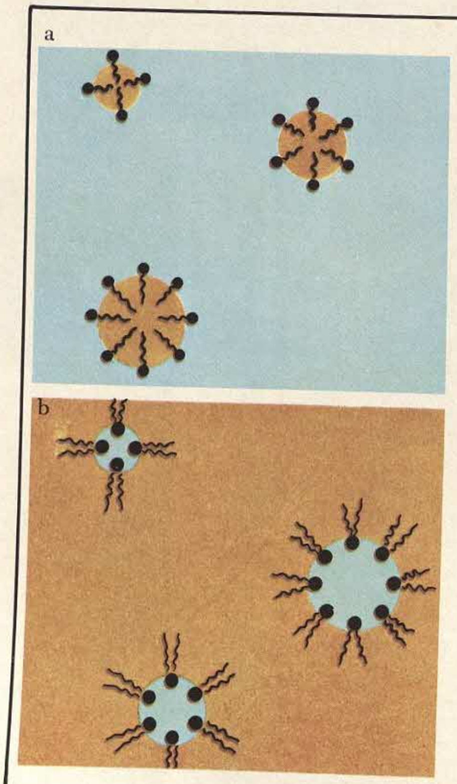
b

2



MICELLES IN EMULSION—The micelles of an emulsified liquid are so large that they can sometimes be seen under a microscope. Even when the addition of emulsifiers causes maximum dispersion, the micelles remain considerably larger than the molecules—even in the case of polymers. The illustration suggests the relative diameters of some molecules and micelles.

can stabilize and the wettability of the emulsifier. Wettability is the capacity of a substance to become dissolved or (in the case of colloids) dispersed in a liquid. It has been found that an emulsifier tends to stabilize an emulsion in which the dispersing phase can wet the emulsifier itself. For example, if the emulsifier is wetted more by the water than by the oil, it will function better in an oil-in-water emulsion; but if the emulsifier is wetted more by the oil than by the water, it will function better in a water-in-oil emulsion. Therefore, the fact that an emulsifier is more readily wetted by one or the other will indicate the phase favored by its molecules and, therefore, the phase that will be stabilized as dispersing medium.



3

PHASE INVERSION — Phase inversion provides an interesting experiment in the field of emulsions. A concentrated emulsion of oil in water, stabilized by the addition of an alkaline soap, is transformed into an emulsion of water in oil by the further addition of alkaline-earth salts. This effect, which can be made apparent by adding a coloring agent that dissolves in oil and is, therefore, effective only when the oil becomes the dispersing phase, results from the formation of alkaline-earth soaps that stabilize emulsions of water in oil. The two illustrations are a schematic representation of this effect. In Illustration 3a, the oil-in-water emulsion is stabilized by an alkaline soap (R—COO—Na); in Illustration 3b, a water-in-oil emulsion is stabilized by an alkaline-earth soap (R—COO—Ca—COO—R).

The alkaline soaps (stearates of lithium, sodium, or potassium), for example, stabilize oil-in-water emulsions; whereas the alkaline-earth soaps (stearates of calcium or magnesium) stabilize water-in-oil emulsions. This results from the fact that in the alkaline soaps most of the wettable surface is provided by the ions, which arrange themselves on the outside of the oily micelle (aggregate of molecules) to be emulsified; whereas in the alkaline-earth soaps the two chains of paraffins linked to the metallic atom form the principal part of the molecule and, therefore, arrange themselves on the outside of the drop to be emulsified, favoring the emulsions of water in oil.

The technical and biological aspects of emulsions are vast. The principal technical uses are in pharmacy and cosmetics, in food preparations, and in many industries, especially leather, textiles, and paper. Oils frequently are emulsified commercially. The main reasons are to dilute the oil, to increase the area of interface, and to modify objectionable physical properties.

THE GASEOUS STATE | a chaotic disorder in nature

Matter exists in three states that are defined in terms of the mobility of the molecules in the particular state. Solids contain molecules that are almost completely restricted in their movement. The atoms and molecules of a solid are held rigorously in fixed positions by strong electrical, chemical bonds. Because nearly all of the kinetic energy of the solid is vibrational, warming a solid causes an increase in this vibration.

A liquid differs from a solid in that the molecules are not held in fixed positions, but are held together by comparatively weak forces of attraction called Van der Waals forces. The molecules in a liquid may move about throughout the liquid, and warming increases this random movement. Molecules in a liquid, therefore, possess translational kinetic energy. If a liquid is sufficiently warmed, the translational movement overcomes the weak Van der Waals forces, and the liquid vaporizes.

A gas contains molecules that are far apart and bound only by the container. The molecules of a gas are in continual random motion. Unlike a liquid or solid, a gas has no definite shape and no definite volume; it expands to occupy its container. Increasing the temperature of a confined gas increases the movement of the molecules and the number of collisions between them. The chaotic nature of matter in the gaseous state requires a rigorous definition of any particular gas sample. It is necessary to define the mass, volume, temperature, and pressure of a gas in order to describe it completely.

PRESSURE, TEMPERATURE, AND VOLUME

It is impossible to isolate any of the properties of a gas, as they are mutually dependent. The temperature of a gas is a measure of its kinetic energy. An increase in temperature causes an increase in the kinetic energy of the molecules in the gas. If the kinetic energy increases, the average speed of the molecules must correspondingly increase. Higher speeds cause molecules of a gas to collide with one another and with the walls of their container more often, and these collisions exert a greater force than collision at lower speeds.

Therefore, with the volume kept constant, an increase in temperature causes an increase in pressure, because the force per unit area on the walls of a container is the measure of gaseous pressure

An increase in temperature causes no increase in pressure if the volume of the container is made larger; the more energetic collisions are spread out over a greater surface, and the pressure remains the same. Charles's law (also known as Gay-Lussac's law) explains that the temperature and volume of a gas are directly proportional, providing the pressure remains constant. A mathematical representation of Charles's law requires that the temperature be measured on the Kelvin (absolute temperature) scale, which has absolute zero—the lowest possible theoretical temperature—for its zero point. All random molecular motion would cease at a temperature of absolute zero under these circumstances.

Charles's law can be expressed mathematically:

$$\frac{t}{v} = \frac{t'}{v'}$$

where t represents the absolute temperature measured in degrees Kelvin, and v represents the volume measured in conventional volume units. This gas law requires that only the temperature and volume be permitted to change—the mass of gas and the pressure must remain constant during this change.

Boyle's law gives the relationship between the volume and pressure of a sample of gas kept at a constant temperature, as follows: The volume and pressure of a given quantity of gas are inversely proportional providing the temperature is held constant. A bicycle tire pump serves as a simple example of Boyle's law. If the outlet of the pump is sealed in such a manner that no air escapes, and the handle is pushed down, the volume of the trapped gas inside the pump will decrease. A measurement of the force required to depress the handle can be compared with the distance that the handle has been depressed. The volume is a measure of the gas remaining, and the pressure is a measure of the force required to compress it. For truly exact results, the tire pump would have to be immersed in a water bath maintained at constant temperature.

Boyle's law can be expressed mathematically: $p\,v = p'\,v'$, where p is the pressure measured in atmospheres or conventional pressure units, and v is the volume measured in conventional volume units. If Boyle's law is used in this form, temperature and quantity of gas must be held constant.

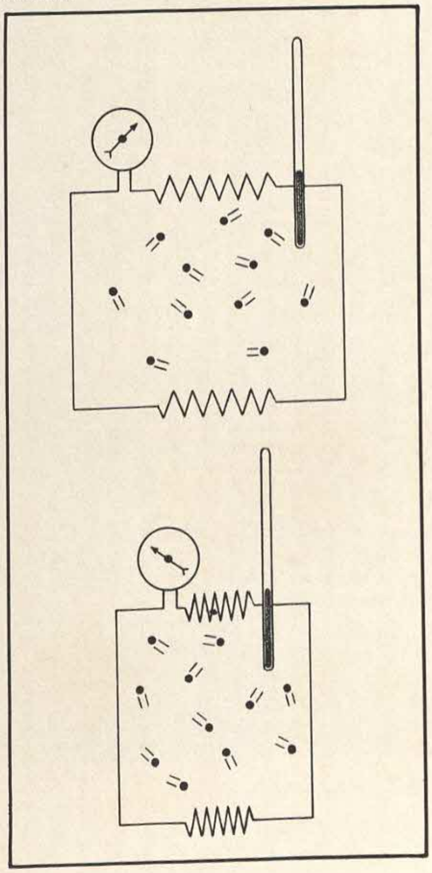
Charles's and Boyle's laws can be combined to form a more workable gas law:

$$\frac{pv}{t} = \frac{p'v'}{t'}.$$

Such a gas law can be used to explain and predict the properties of a given sample of gas even though pressure, temperature, and volume are allowed to vary independently.

THE DIFFERENCE BETWEEN REAL AND IDEAL GASES

Boyle's and Charles's laws are used to describe real gases at temperatures and pressures that are neither extremely high nor low. These laws hold for an ideal gas, which is indeed defined as one that obeys these laws. An ideal gas, however, must include some confining assumptions: its molecules must exhibit no intermolec-



BOYLE'S LAW—The volume and pressure of a fixed quantity of gas are inversely proportional at constant temperature. This law is named in honor of the English physicist and chemist Robert Boyle, who carried out extensive experiments on the behavior of gases.

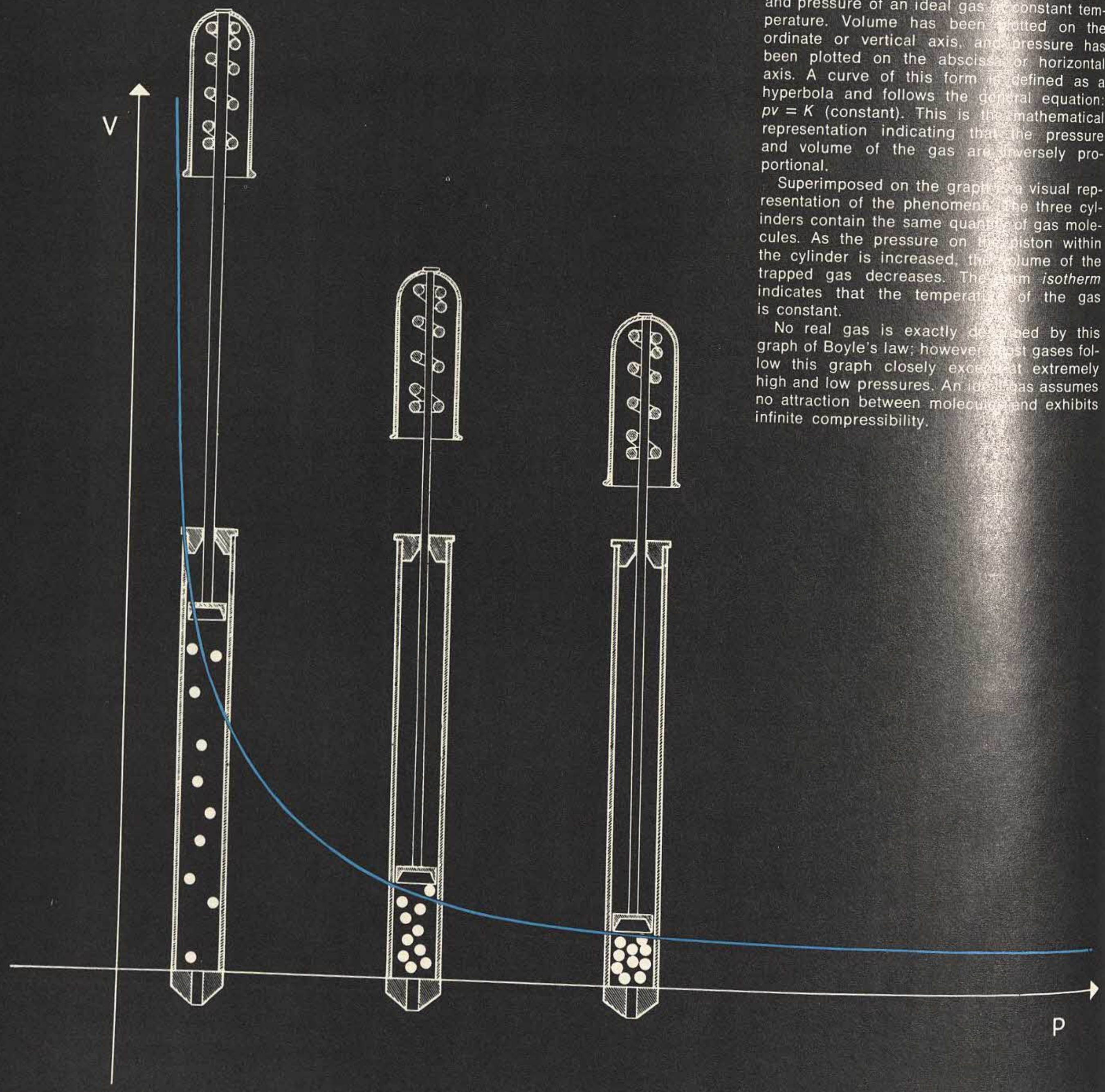
The illustration shows two containers holding the same quantity of gas. The thermometers indicate that the temperatures of the containers are equal; however, the pressure of the lower container is higher than the pressure of the upper container due to the decreased volume.

ular attractions, and the gas must be infinitely compressible. Intermolecular attractions are weak in gases, but they are nevertheless present in the form of Van der Waals forces. If a gas were infinitely compressible, it would disappear completely at great pressures. Real gases can be compressed only until the spaces between the molecules have been exhausted. Gaseous behavior ceases when the molecules are held extremely close together.

Equations have been developed that describe the behavior of real gases. These equations are complex and they differ for individual gases. The Van der Waals equation for real gases, used to describe any real gas at any temperature and pressure, is stated in the equation

$$\left[p+\frac{n^2a}{v^2}\right](v-nb)=nRT$$

where p is pressure, v is volume, T is temperature in °K, n is the number of moles, R the universal gas constant, and a and b the constants for the particular gas involved.



THE IDEAL ISOTHERM—The blue line represents the relationship between the volume and pressure of an ideal gas at constant temperature. Volume has been plotted on the ordinate or vertical axis, and pressure has been plotted on the abscissa or horizontal axis. A curve of this form is defined as a hyperbola and follows the general equation: $pv = K$ (constant). This is the mathematical representation indicating that the pressure and volume of the gas are inversely proportional.

Superimposed on the graph is a visual representation of the phenomena. The three cylinders contain the same quantity of gas molecules. As the pressure on the piston within the cylinder is increased, the volume of the trapped gas decreases. The term *isotherm* indicates that the temperature of the gas is constant.

No real gas is exactly described by this graph of Boyle's law; however, most gases follow this graph closely except at extremely high and low pressures. An ideal gas assumes no attraction between molecules and exhibits infinite compressibility.

GAY-LUSSAC'S LAW

the ideal road to the absolute

To many students, physics sometimes seems one long litany of laws with the name of a scientist attached to each discovery. However, the laws can take on the appearance of links in a chain, for one man's discovery often is the basis for another man's research and discovery.

Boyle's law, for example, interprets the behavior of a gas when its pressure and volume vary while the temperature is kept constant. A natural follow-up investigates what happens when the volume is kept constant while the temperature is varied. The apparatus to be used in this experiment is shown in Illustration 1. It consists of a graduated glass cylinder, closed at the top by a stopcock; its bottom is connected, by means of a rubber tube, to a second glass cylinder that is open. Because of the principle of communicating vessels, the mercury reaches the same level in both cylinders; the upper part of the first cylinder, between the meniscus of the mercury and the stopcock, is full of gas (air, in this case). Once the system is set up, it is allowed to stand until each of its parts assumes the temperature of the environment.

When this point of equilibrium is reached, the temperature and pressure are noted with the help of a manometer and a thermometer. The value disclosed by the manometer is indicated by P_0 (initial pressure); and the value shown by the thermometer by t_0 (initial temperature). The graduated cylinder is then enclosed in a sleeve and the temperature of the gas is raised from t_0 to t. The gas molecules will now increase their speed of motion (kinetic energy), striking the walls of the cylinder more frequently and with greater force; the pressure of the gas, therefore, increases. Next, the temperature is raised by 10° C (for example, from 20° to 30° C). The volume of the gas is kept constant by raising the second cylinder as much as necessary to keep the mercury in the first cylinder at the same level. (In fact, as the gas expands, it will continue to depress the level of the mercury.) A glance at the manometer will show that the pressure has passed from one atmosphere to 1.0365 atmospheres. How much has the pressure increased per degree of temperature change? Gay-Lussac's law, formulated in 1802 by the French chemist Joseph Louis Gay-Lussac, gives the answer. The law states that the final pressure is equal to the initial pressure plus a certain fraction for each degree of increased temperature. This fraction amounts to 1/273 of the initial pressure for each degree of temperature. The law is written in this way:

$$P_t = P_0(1 + \beta t)$$

where β is 1/273 or 0.003663 and t is the temperature change; β has the same value for all gases, irrespective of the chemical nature of the gas or the temperature in-

GAY-LUSSAC'S LAW—This apparatus makes it possible to verify the variations of the volume and pressure of a gas with variations of the temperature.

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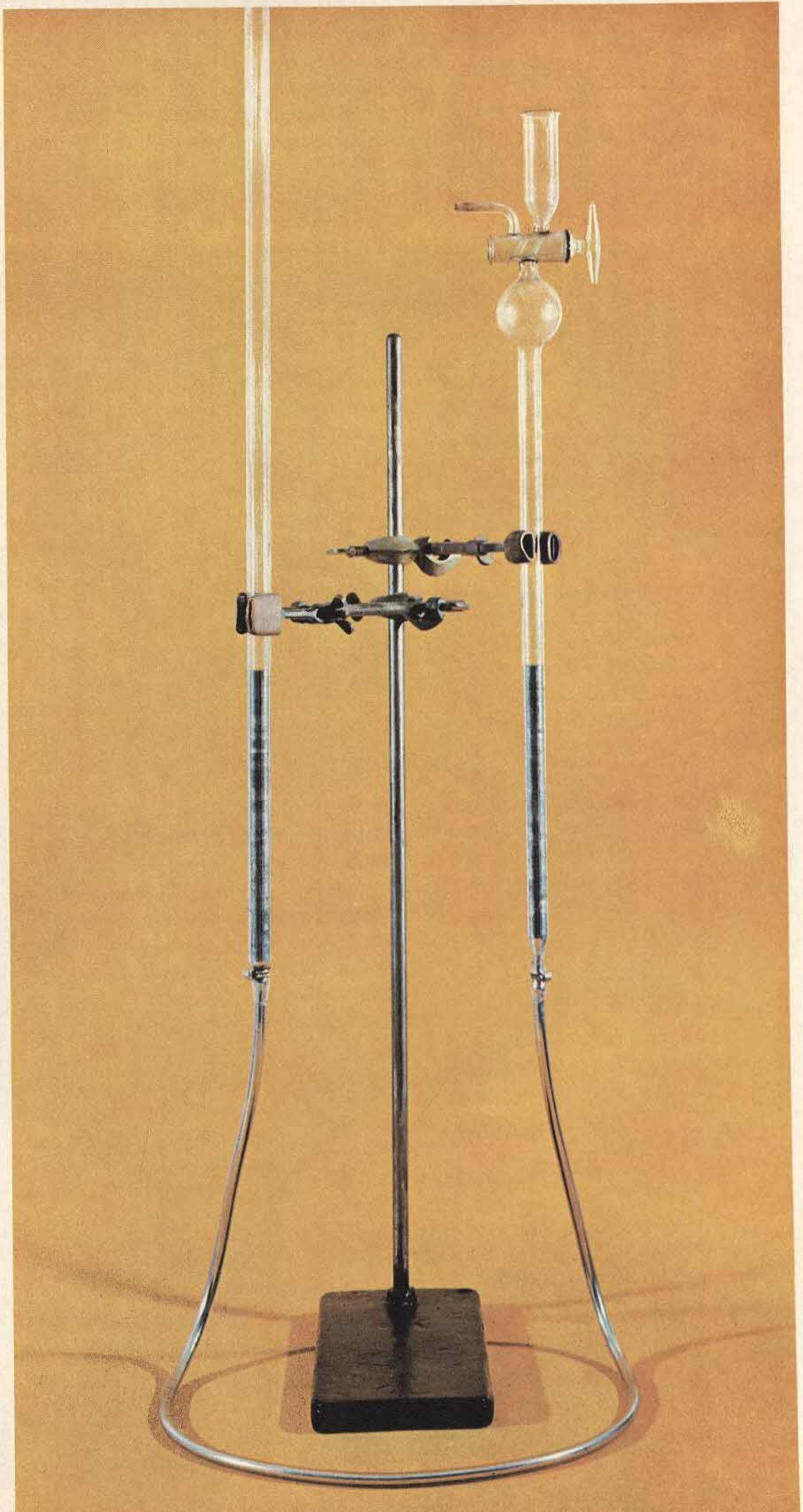
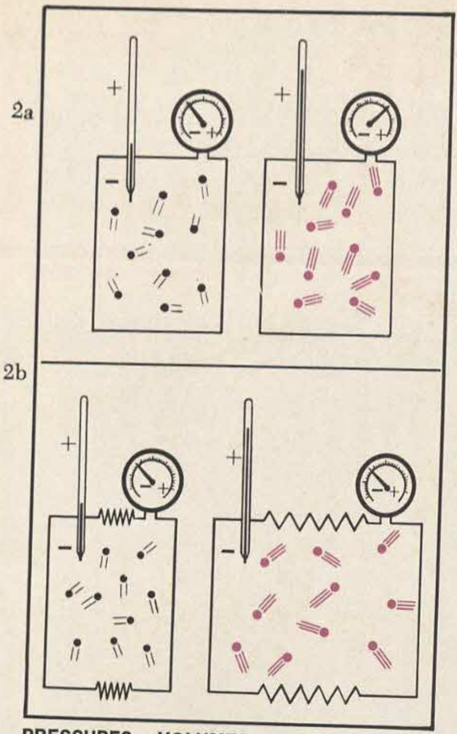




PRESSURES, VOLUMES, AND TEMPERATURES—The thermometer and manometer readings in Illustration 2a show that if the volume remains constant, an increase in the temperature causes an increase in the pressure of the gas. If the pressure remains constant, an increase in the temperature of the gas will cause an increase in the volume of gas (Illustration 2b).

terval. Suppose another experiment is tried, using the same apparatus. This time the pressure is kept constant by displacing the second cylinder in such a way that the mercury will always be at the same level in the two branches. The gas again is heated, causing it to expand; as it expands it pushes the mercury down as long as the pressure remains constant.

If the same calculations used before to find the pressure are now repeated, the increase of volume per degree of temperature can be found for every type of gas.

The final volume V_t will therefore be given by:

$$V_t = V_0(1 + \alpha t)$$

where α is practically equal to β. In other words, the pressure and the volume of the gases vary according to the same coefficient (1/273) for each degree of temperature variation.

These experiments show how the pressure and volume of a gas vary as functions of the temperature. The next step is to evaluate the significance of these expressions and see what actually is hidden beneath these formulas.

Two cylinders, each filled with an ideal gas, are needed. An ideal gas is used simply because it is convenient; since the experiment calls for very low temperatures, the use of an ideal gas avoids the problem of liquefaction. The piston of the first cylinder is fixed; the gas is then heated. As the temperature is increased, the values of the rising pressure are noted from the manometer. The same operation is carried out with the second cylinder, except that the piston is left free to slide. This time the rise in temperature causes an increase in the volume of the gas. These values are also noted. What will happen when both cylinders are cooled? In the first cylinder the pressure will fall to zero, while in the second the piston will move into the cylinder until the volume is completely annulled. There thus exists a temperature at which both volume and pressure drop to zero. The task now is to determine the exact value of the temperature at which this happens. First, the pressure, volume, and temperature data noted in the experiment are plotted (Illustrations 3a and 3b). In these graphs, the values of the temperature are placed on a horizontal line, the abscissa, while the values of the volume and pressure are placed on a vertical line, the ordinate. It will be seen that all the data lie on the same straight line that intersects the abscissa at a temperature of −273.16° C (about −459° F). Stated simply, this means that at this value of the temperature, the pressure and volume have a value of zero.

Thus, −273.16° C represents the lowest temperature that can be reached. At lower temperatures, in fact, negative values of pressure and volume would result. This value of the temperature, therefore, takes the name of absolute zero. The true significance of absolute zero can be seen, given the facts already learned. It was stated earlier that the temperature of a body represents the state of motion of its molecules. Therefore, the pressure is completely annulled at the very moment when there is no longer any molecular motion within the gas, when the impacts against the walls have disappeared. The temperature of the gas is also zero, because all thermal movement of the molecules has stopped. If the experiment had been carried out with a real gas, absolute zero would not have been reached because the gas would have liquefied before it had dropped all the way to absolute zero. All the same, if the data were plotted to the point of liquefaction, they again would be found to lie on a straight line which could be projected until it cut the abscissa.

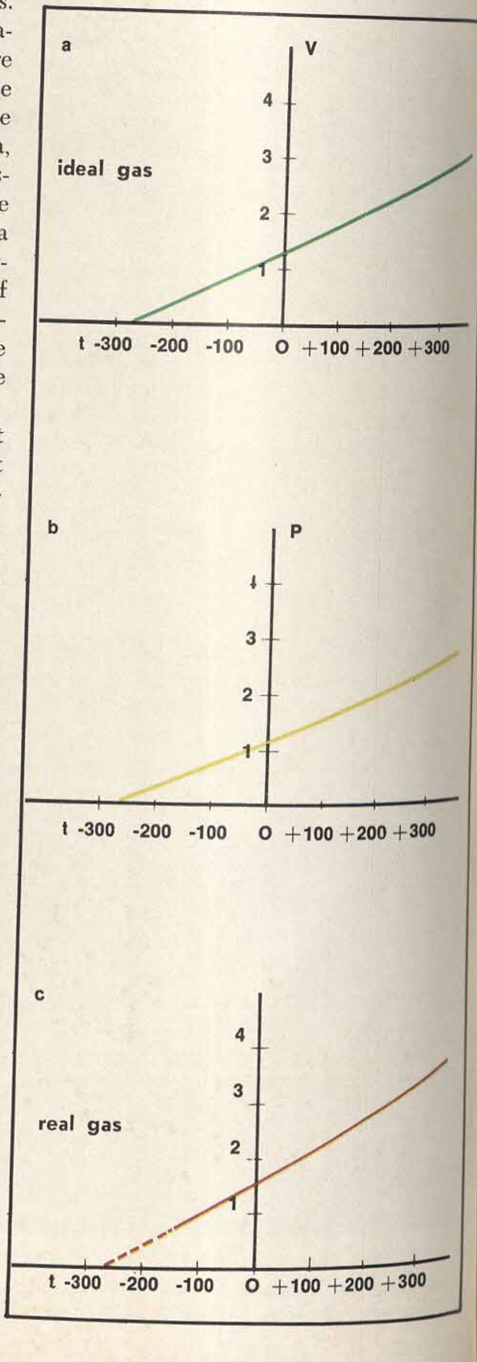
This points to a completely new temperature scale: the absolute scale, also known as Kelvin's scale. The zero of this scale, obviously, lies at −273.16° C.

ISOBARS AND ISOCHORS—In Illustration 3a, temperatures are plotted as abscissae and volumes as ordinates. The data collected define a straight line that intersects the abscissa at −273.16° C. The straight line is an isobar because it is constructed with data obtained at constant pressure.

In Illustration 3b, the temperature is plotted as an abscissa, and pressures are plotted as ordinates. The data collected from measurements carried out at constant volume again define a straight line that cuts the abscissa at −273.16° C. This straight line is called an isochor.

If a real gas is used in the experiment, the gas will liquefy at a certain point, and the straight line representing the experimental data, therefore, will not reach far enough to intersect the abscissa; however, if this line is prolonged, it also will intersect at −273.16° C (Illustration 3c).

3



DISSOCIATION OF GASES | molecules resulting from chemical change

In 1811, a fundamental law of physics was stated by the Italian physicist Amedeo Avogadro: at constant temperature and pressure, equal volumes of all gases contain the same number of molecules. This law is important in explaining how, under some circumstances, the volume of a gas may increase to an extent that cannot be attributed merely to the increase in temperature.

The cause may be dissociation: the formation of two or more molecules where only one had existed before, necessarily resulting (in accordance with Avogadro's law) in greater volume. Concomitant chemical changes will also indicate that essential alterations have occurred in molecular structure.

If copper is treated in a laboratory with concentrated nitric acid, one of the products will be nitrogen dioxide: $Cu + 4HNO_3 \rightarrow Cu(NO_3)_2 + 2H_2O + 2NO_2$. If the reaction occurs at moderate temperatures, however, the gas formed will be the colorless dinitrogen tetroxide: N_2O_4.

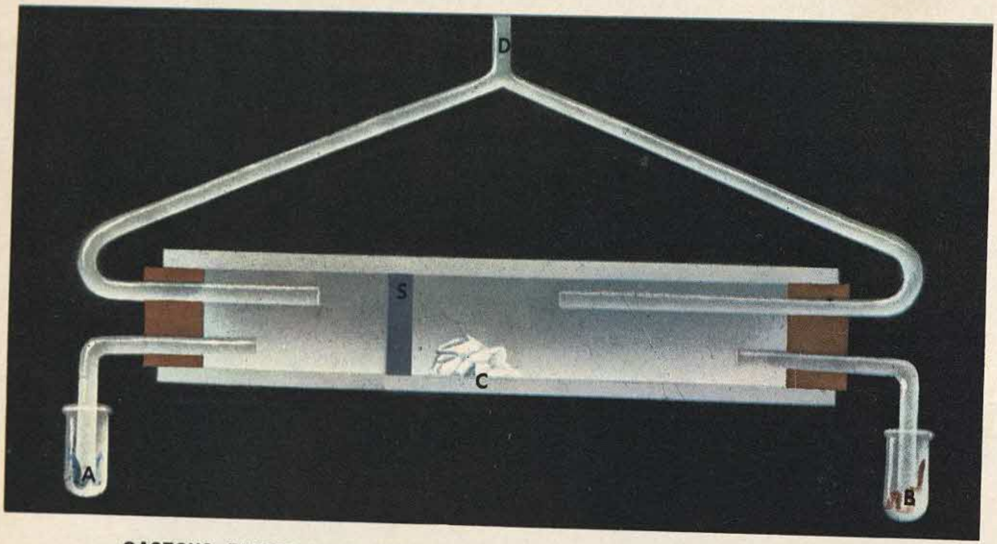
An increase in temperature to about 60° C (140° F) will cause the gas to take on a reddish-brown hue, showing that it is dissociating into nitrogen dioxide, NO_2; at 156° C (about 312° F) the dissociation is about complete. Although both dinitrogen tetroxide and nitrogen

DISSOCIATION OF SULFUR — The naturally occurring sulfur molecule is composed of eight atoms; that is, it is octatomic, with a molecular weight of 256. At a temperature of about 1,000° C (1832° F), it is composed of two atoms; that is, it is diatomic, with a molecular weight of 64. In the upper left of the illustration the octatomic molecule is shown; with an increase in temperature, this is dissociated into four diatomic molecules.

dioxide have the same composition, in the sense that each is composed of molecules with two atoms of oxygen for every atom of nitrogen, yet with the increase in temperature the number of molecules will have doubled, also doubling the volume, and the chemical characteristics will have altered.

Many other substances, such as hydrogen iodide, ammonia (NH_3), phosphorus vapor (P_4), and iodine, also undergo dissociation at high temperatures. It should be noted that the reactions are reversible—that is, by cooling the gas, the molecules will recombine: $2NO_2 \rightarrow N_2O_4$; and for this reason, in the synthesis of ammonia by the Haber method the control of temperature is of major importance; in the reaction $N_2 + 3H_2 \rightleftarrows 2NH_3$, only careful control will shift the equilibrium to the right, to form the desired product.

If sulfur, with its usual octatomic molecule (S_8), is heated to 1,000° C (1,832° F), the molecules become diatomic (S_2); that is, for every earlier molecule with eight atoms there will be four molecules, each with two atoms. Similarly, phosphorus with its tetratomic molecule becomes diatomic ($P_4 \rightarrow 2P_2$). Obviously, it would be impossible to determine the molecular weight of these substances by measuring the density of their vapors, for this would vary according to the proportion of molecules of each kind found in the volume of gas being measured. If a scientist were not aware of the phenomenon of dissociation, he could easily make errors in determining density. In the dissociation of ammonium chloride (NH_4Cl) into hydrochloric acid (HCl) and ammonia (NH_3), for example, two molecules are produced where there had been only one molecule; because double the original volume is occupied, and because density and, therefore, weight are inversely proportional to volume, it is clear that half the actual molecular weight would be obtained.



GASEOUS DISSOCIATION—This experiment requires an arrangement of tubes as shown in the illustration, a specimen of sal ammoniac (ammonium chloride), and some litmus paper. Litmus is a substance that changes color in the presence of various substances: in the presence of an acid, it turns red; in the presence of a base it turns blue. In the laboratory it is usually used as a coating on filter paper, which is therefore called litmus paper.

The ammonium chloride is placed in the large tube **C**, which has been divided by a porous plug **S.** In the small tube **A** on the left side is placed a strip of litmus paper already turned red by contact with an acid; another strip, turned blue by contact with a base, is placed in the small tube **B**, on the right side. An inert gas is circulated in tube **D**, and the ammonium chloride is heated. Soon the red strip of litmus paper in tube **A** turns blue, and the blue strip in tube **B** turns red.

By heating the ammonium chloride, the salt was dissociated into ammonia, a base, and hydrochloric acid, obviously an acid ($NH_4Cl \rightarrow NH_3 + HCl$). Ammonia is lighter than hydrochloric acid. According to Graham's law, the diffusion rates of gases are inversely proportional to the square root of their density; therefore, the lighter ammonia diffuses more rapidly through the porous plug, and an excess of the base collects there, thus leaving an excess of acid on the right side of the large tube. The presence of these is indicated by the changes in the colors of the litmus paper on each side. The experiment illustrates the dissociation of the vapors of ammonium chloride into molecules of ammonia and hydrochloric acid.

It must not be assumed, however, that complete dissociation always occurs. This is extremely unlikely; the transition is gradual, and it is more correct to refer to a degree of dissociation at any given temperature and pressure. As the temperature increases, so does dissociation; more and more of the molecules are dissociated, and at rather high temperatures—depending on the particular gas—complete dissociation may occur. Nor is dissociation invariably accompanied by an increase in volume; in the dissociation of hydrogen iodide, for example, molecules of iodine and hydrogen are formed with no increase in volume. If dissociation occurs in a closed space whose volume is kept constant, a corresponding increase in pressure will occur; a substantial increase in pressure retards the dissociation. On the other hand, rarefaction, or a reduction of density, fosters dissociation. It may be said that an excess of one of the products of the dissociation may have the effect of regressing the dissociation.

In the case of the ammonium chloride reaction, for example, two concentrations—that is, quantities of a substance within a given volume—of the products of dissociation (ammonia and hydrochloric acid) may be considered: c_1 and c_2. The concentration of the nondissociated molecules of ammonium chloride may be represented by C, while K represents a constant at a constant temperature. The following mathematical expression links these magnitudes in this general relation: $c_1 \times c_2/C = K$. This may be rewritten as either $c_1 = KC/c_2$ or $c_2 = KC/c_1$; that is, an increase in either one of the products of dissociation must produce (K remaining constant) an increase in the undissociated molecules and a decrease in the other product of dissociation. In other words, the concentration of nondissociated molecules increases and the degree of dissociation regresses. This equation actually exemplifies a particular case of the law of mass action, which states that the active masses of the substances determine the rate of a chemical reaction.

THE KINETIC THEORY OF GASES

the confused motion of molecules

When presidential advisors speak on the nation's economy, they are dealing with a massive, overall fact of life that touches each and every individual. To understand the economy and control it to some degree, however, they must delve into the myriad complexities—prices, wages, supply, demand, and many more—that shape and affect the economy. In short, to know and understand something as huge and complex as the economy, a person has to study the many things that make it what it is. Analogously, there are many experiments confirming the fact that matter is made up of particles. So, to gain a more detailed knowledge of just what constitutes matter, an investigation is called for to probe the properties that matter possesses because of the simple fact that it consists of these particles. For example, those properties of matter that are visible, external, and macroscopic can be studied. Of course, the quantities of matter examined in this way must be large enough to be handled and subjected to laboratory experiments.

Some of the properties of a large substance that can be easily measured are its color, the ease with which it conducts heat, its hardness, and its specific weight. However, the study of matter also can be undertaken in a completely opposite manner: since it is known that matter is made up of atoms—of minute submicroscopic particles—an experimenter can investigate the elementary properties of these particles and then imagine how they might be bound together, and what properties they might possess when they are united.

It is fairly obvious that these idealized assemblages of particles, at least in their imagined form, must be different from the matter which can be readily observed in macroscopic quantities. Nevertheless, the fact that the properties have been imagined by means of hypotheses suggested by a model may subsequently lead to the discovery of new and interesting properties of matter through experimentation; or, the process may simply help interpret properties that are already known.

Two different starting points can be used to examine, through deduction, the properties of matter. The first method postulates that the simplest types of matter to study are the gases. Actually, it is easier to deduce the properties of gases than the properties of liquids or solids, at least in theory. The second postulates that some simple properties of atoms and molecules make it possible to imagine the properties that must be possessed by large groupings of these particles.

In the latter method the attempt is made to interpret the macroscopic properties of matter on the basis of the behavior of its microscopic and submicroscopic constituents.

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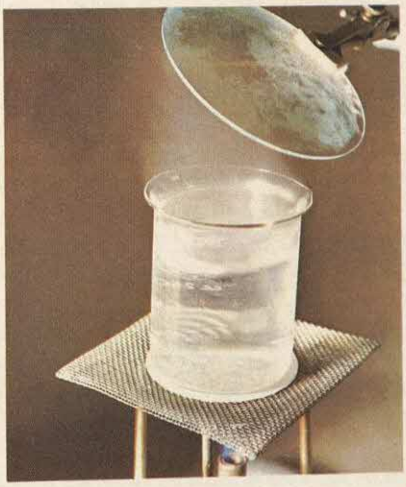


SOLIDS, LIQUIDS, AND GASES—Gases obtained by the sublimation of solids or evaporation of liquids have a much smaller density than that of the condensed body that gives rise to them. If a quantity of water that has a density of about 1 is evaporated, vapor is obtained; this vapor, which is a substance in the gaseous state, has a density about a thousand times smaller than the original quantity of water. In fact, the vapor will condense as it strikes a cold surface; if the speed with which the vapor strikes the surface is quite high, the vapor will be transformed into a few droplets of water. Thus, water and vapor are the same substance and consist of the same molecules; however, these molecules are separated by much greater distances in the vapor than they are in either a solid or a liquid.

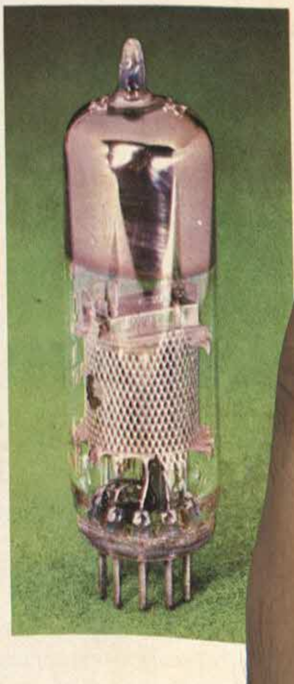
2

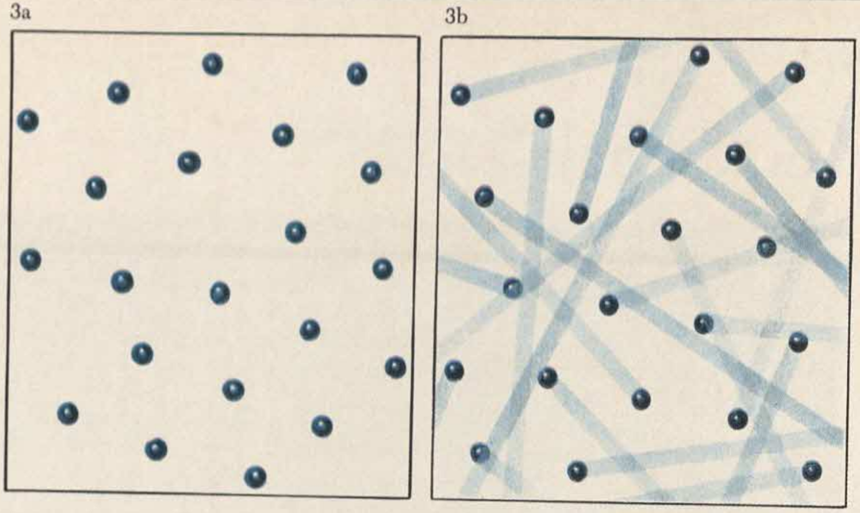
COMPRESSED GASES AND RAREFIED GASES—The gas in a cylinder or tire (Illustration 1a) is highly compressed. This gas can be thought of as an evaporated solid, and it follows that its molecules now are more rarefied than they are in their solid form. Nevertheless, the molecules can be brought closer together or spread farther apart simply by varying the volume of the container enclosing them.

A rarefied gas can be observed, although indirectly, in this vacuum tube (Illustration 2b). Actually, the air inside the tube is at a pressure (and therefore at a density) of about a billion times less than that of atmospheric air. This means that a gas has the property whereby its molecules can become separated by really great distances; in fact the molecules of a gas not enclosed are unlimited in their movements.

a

b





A GAS MODEL—At this point it is possible to sketch a model of a gas made up of something similar to molecules. In this instance, the model consists of idealized particles (Illustration 3a). The molecules of the gas can be imagined as small spheres (although they may actually have a different form), distributed in a given volume, distant from one another but filling the volume in a homogeneous manner. The volume will contain much empty space, since the spheres are sufficiently small that they occupy only an extremely small part of the total volume.

This model of the gas is rather imperfect, and it may be well to imagine how it can be improved. Actually, it is difficult to imagine the molecules remaining immobile (as illustrated) and maintaining their distance from each other; they are subject to the force of gravity and, therefore, would fall. It might be supposed that they would behave like inelastic bodies or like bodies made up of a material having the same consistency as modeling clay. However, such a hypothesis can be rejected immediately; if it were true, the gas would, in a moment, reduce itself to a heap of atoms or molecules and would once again have the properties of a solid.

The true hypothesis, therefore, is just the opposite. It assumes that the molecules are elastic and that their movements are characterized by the property of perfect rebound when they collide with each other or with the walls of a container. Even if it is imagined that their number is small, it is obvious that these molecules will not be able to fall and strike the bottom of the container without colliding with each other. Their movements, therefore, will be quite disorderly. The model of the gas thus could be the one shown in Illustration 3b where the molecules, represented by the small spheres in continuous and disorderly movement, collide with each other and with the walls of the container.

The results obtained from such analysis have been translated into formulas and organized into a theory known as the kinetic theory of gases. This theory was first used to interpret the properties of gases; later it was generalized and applied to the study of liquids and solids.

An ideal gas, as studied in Illustration 3, does not actually exist, although some gases behave in a like manner because their molecules have similar properties. The properties of an ideal gas can be predicted mathematically as to the mechanical properties of an assembly of such ideal particles. Gases not having these properties under ordinary conditions, however, will display them under particular conditions.

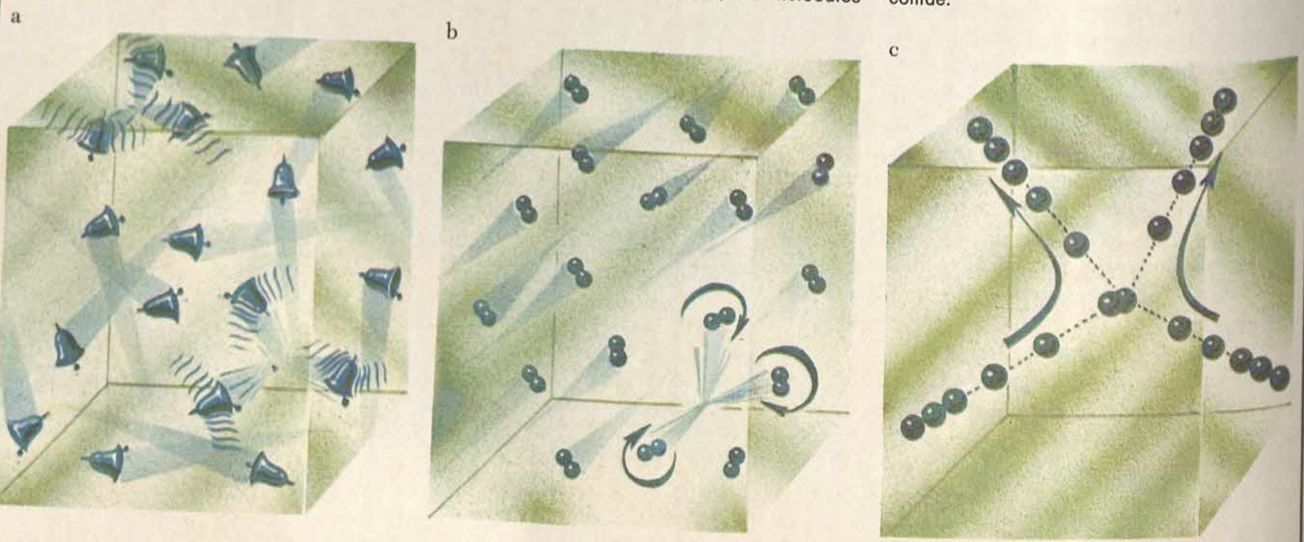
4

SOME PROPERTIES OF THE MOLECULES—The next task is to try to examine the properties of the spheres discussed in the explanation of Illustration 3. As for the container, it is easy to think of it as a small box with elastic walls into which are thrown some highly elastic steel balls (similar to those found in a ball bearing). In this case, however, the fact that the steel balls are not perfectly elastic would ensure their falling to the bottom, where they would remain, grouped closely together and forming a layer of a certain thickness.

The molecules of a gas, therefore, must be far more elastic than such steel balls. Nevertheless, the molecules are not ideally elastic spheres; after each collision, in fact, they will not conserve all the energy they had before.

Suppose some small bells and clappers are enclosed in a box whose walls are perfectly hard and elastic. The bells, in continual motion, collide with each other and with the walls of the box. At each collision they receive kinetic energy that is transformed immediately into a movement of the bell as well as a vibration. The vibration is radiated into space and therefore lost; in the end it will no longer be found among the bells in the box (Illustration 4a). The same thing happens to the molecules. First of all, very often they are not perfectly spherical but elongated (like those of air, for example), because they consist of two atoms that can vibrate about their positions of equilibrium according to the impacts they receive (Illustration 4b). Furthermore, the molecules have the property of radiating a part of their vibration or rotational energy in the form of electromagnetic waves. Therefore, as with the bells, the energy available in a box filled with molecules can be lost into space, carried away by the light waves radiated by the molecules themselves (the most common example is infrared radiation). The end result is that after a short while the molecules come to rest on the bottom of the box, thus losing the characteristics of a gas. Under ordinary laboratory conditions this does not occur; the molecules remain in the box and collide with its walls. These walls, heated to environmental temperature, keep the molecules in motion by means of a special mechanism. This is one of the reasons a gas cools if left to itself at a temperature higher than that of the environment.

Lastly, the molecules attract each other (Illustration 4c). The proof of this is found in the fact that a solid is capable of resisting tension, and that liquids behave as if they were covered by a membrane formed by molecules; this in turn exerts a tension and tends to enclose the liquid, thereby causing the formation of drops. The molecules do not possess these properties simply because they find themselves within a solid or liquid; they also possess the properties when they are spread apart, forming a gas. Quite naturally, in this case the attractive forces make themselves felt only when the molecules are particularly close together, as when the gas is highly compressed or when two molecules are about to collide.



CHARACTERISTICS OF THE PERFECT GAS

studying the properties of molecules

A man may never have been to Washington, D.C., yet he may have considerable knowledge about the city, its federal buildings, streets, parks, and people. He may have gained this knowledge from books, maps, or persons who have been there. In short, he has made use of available sources of information to brief himself on something he has not seen or experienced. In a somewhat similar way, some of the microscopic (invisible) characteristics of a gas may be learned from observing those properties of the gas that are macroscopic (visible). An observer can also deduce that the molecules of which the gas consists are in continuous movement.

The objective is to determine what systems can be used to find out how many molecules are contained in a unit volume of any gas at a pressure of one atmosphere and a temperature of 20° C (68° F). A study of the kinetic theory of the perfect gas is invaluable.

Actually, a prime reason for studying the kinetic theory of gases (and, more generally, that of matter) is that the theory provides the only way in which the world of the molecules can be understood. No microscope can show the molecules of a gas, and no instrument can carry out an experiment on a single molecule. The only way man can penetrate the world of the molecules is by: (1) theorizing how it may be constructed; (2) deducing what properties it must possess, based on what has been imagined; and (3) comparing what has been deduced with the results of experiments and observations. If a scientist's deductions are confirmed by relevant experiments and observations, he will know that they are correct and that matter is really made up as he had theorized. On the other hand, if his deductions are not confirmed, he will have to change his hypotheses in a way that will enable him to gain a better, although indirect, understanding of the structure of matter. Little by little, as he enters deeper into the world of the atom, he will be forced to make more and more frequent use of this method of research. It is essentially a theoretical method because it makes use of mathematical and mechanical models of matter.

The kinetic theory of gases makes it possible to explain many of the characteristics of gases and to interpret known laws. A study of some important prop-

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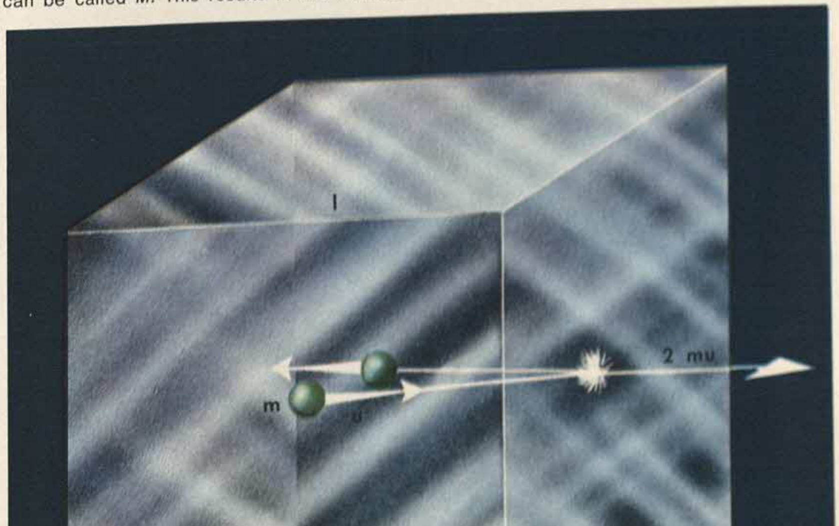
PRESSURE—If a gas can be imagined as an assembly of spherical elastic particles that are in continual motion and therefore collide with one another, it can also be supposed that the pressure exerted by the gas against the walls of a box within which it is confined is due to the constant impact of the molecules against these walls. This hypothesis is correct, and the kinetic theory of gases makes it possible, with simplifications, to calculate the relationship that exists between the speed of the molecules and the pressure exerted by the gas against the walls confining it.

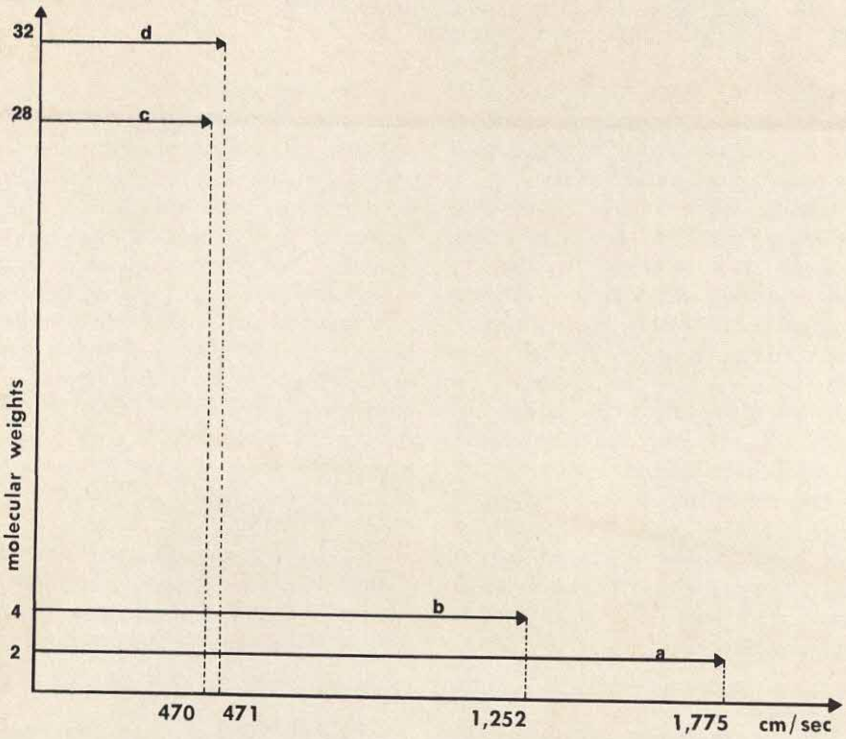
As shown in the illustration, a box in the form of a cube contains molecules of a gas. Each of these molecules moves at its own particular speed, but it may be supposed that the average velocity of all the molecules is u. The molecules, in general, will move in some oblique direction with respect to the faces of the cube; however, their displacements can be resolved into three perpendicular components parallel to those faces. The length of the side of the cube is represented by l. The molecules that move in a predominantly horizontal direction will cover the whole length of the cube relatively quickly; in one second they can cover it u/l times. When they reach one end of the cube, they collide with the face and are bounced backward. On a single face of the cube this will occur $u/2l$ times per second. Every time a molecule strikes the face of the cube, this face receives an impulse equal to twice the momentum possessed by the molecule prior to the impact. In fact, the molecule does not come to a stop; rather, it continues to travel in the opposite direction at the same velocity as before. Since the momentum is expressed as the product of the mass of the molecule and its velocity, the impulse received at each impact amounts to $2mu$, where m is the mass of the molecule. If n molecules have been placed inside the cube, the total impulse received by one face during a period of one second will be $1/3 \times 2nmu \times u/2l = 1/3 \times nmu^2/l$ (the factor 1/3 accounts for the fact that the impacts are distributed in three directions.

This expression represents the total change of moment impressed on the molecules by one face of the cube or the force that the face exerts on the molecules; this force, distributed over the face of the cube, which has an area l^2, is nothing other than the pressure p of the gas. The value of the force is, therefore, $pl^2 = 1/3 \times nmu^2/l$. This equation also can be written: $p = 1/3 \times nmu^2/l^3 = 1/3 \times nmu^2/V$ (in fact, the volume of the cube is equal to the cube of the length of its side). If m is the mass of one molecule, mn represents the mass of the whole gas enclosed in the box and this can be called M. This results in the formula: $p = 1/3 \times Mu^2/V$.

The entire process shows how the kinetic theory makes it possible to calculate the exact pressure a gas exerts on the walls of the container it occupies when the following facts are known: (1) the size of the container; (2) the mass of the gas put into it; and (3) the average velocity of the molecules that make up the gas.

Since this formula can be verified experimentally, it is possible to measure the velocity of the molecules with the aid of a special apparatus. The experiment thus confirms the theoretical predictions.





THE VELOCITY OF THE MOLECULES—The formula deduced in the explanation of the preceding illustration makes it possible to evaluate the average velocity of the molecules in a gas. Since the formula has been proved correct, it can be used to obtain a solution for *u*, thereby expressing the velocity of the molecules in terms of the mass of the gas, the volume it occupies, and the pressure it exerts on the walls of the container in which it is enclosed. Actually, the formula for the first illustration can be written:

$$u = \sqrt{3pV/M}.$$

Here is an example. To calculate the speed in the case of hydrogen, the various magnitudes will have to be replaced by their numerical values. All the values must be expressed in the units of the same system of measurement. In this case, then, the formula reads: $M/V = 0.0000896$ g/c^3; if the gas is imagined at atmospheric pressure, $p =$ about 1,000,000 dyne/cm^2. Therefore, $u = 3{,}000{,}000/0.0000896$ = about 184,000 cm/sec = 1,840 m/sec.

In this illustration, arrows of different lengths are used to indicate the velocities of the molecules of various gases: **a** represents hydrogen, **b** helium, **c** nitrogen, and **d** oxygen. With the molecular weights shown against each arrow, it can be seen that the average velocities are inversely proportional to the square root of the mass. It should be kept in mind that the velocities shown are for the real molecules of these gases; in some cases these molecules consist of two atoms (in hydrogen, oxygen, and nitrogen, for example). There also are gases whose molecules consist of three or more atoms.

erties of perfect gases has its own niche in this scientific pursuit.

APPLICATIONS OF THE MOLECULAR BEAM TECHNIQUE

The molecular beam technique almost succeeds in isolating the molecules and determining their characteristics one by one. It has a large number of applications in many branches of science and technology. For example, this technique is widely used to study the properties of gases that manifest themselves when gases collide at high supersonic velocities with the outer surfaces of an aircraft; it thus becomes possible to observe the phenomena that occur in so-called hypersonic flight.

The same technique is used for studying neutrons, for they too can be studied according to their different velocities by means of an apparatus similar to the molecular beam technique.

HOW THE VELOCITY OF THE MOLECULES IS MEASURED—By using a reasoning process analogous to the one used in explaining the preceding illustrations, the velocity distribution of the molecules can be calculated. In other words, it is possible to find out what percentage of the molecules possess a velocity lying between 0.1 and 0.2 of the average velocity; also, how many other molecules have a velocity of between 0.2 and 0.3, and so forth. These calculations can be continued until they reveal how many molecules have velocities much greater than the average velocity. However, these calculations are rather complex; therefore, it may be simpler to see how these velocities can be measured in practice. The technique used involves molecular beams, and to measure them a velocity selector (illustrated) is used.

The letter **a** indicates the source of the molecules (or atoms). The problem is to discover the velocity distribution of the atoms that escape from a drop of fused silver; in other words, to determine the velocity of the atoms of silver vapor. The silver is attached to a piece of tungsten wire bent as shown and heated until it fuses. Innumerable molecules will escape from the drop adhering to the tungsten wire and disperse in all directions at different velocities. Some molecules will move slowly, others rapidly. Before searching out the slow and fast molecules, however, it is necessary to produce a molecular beam.

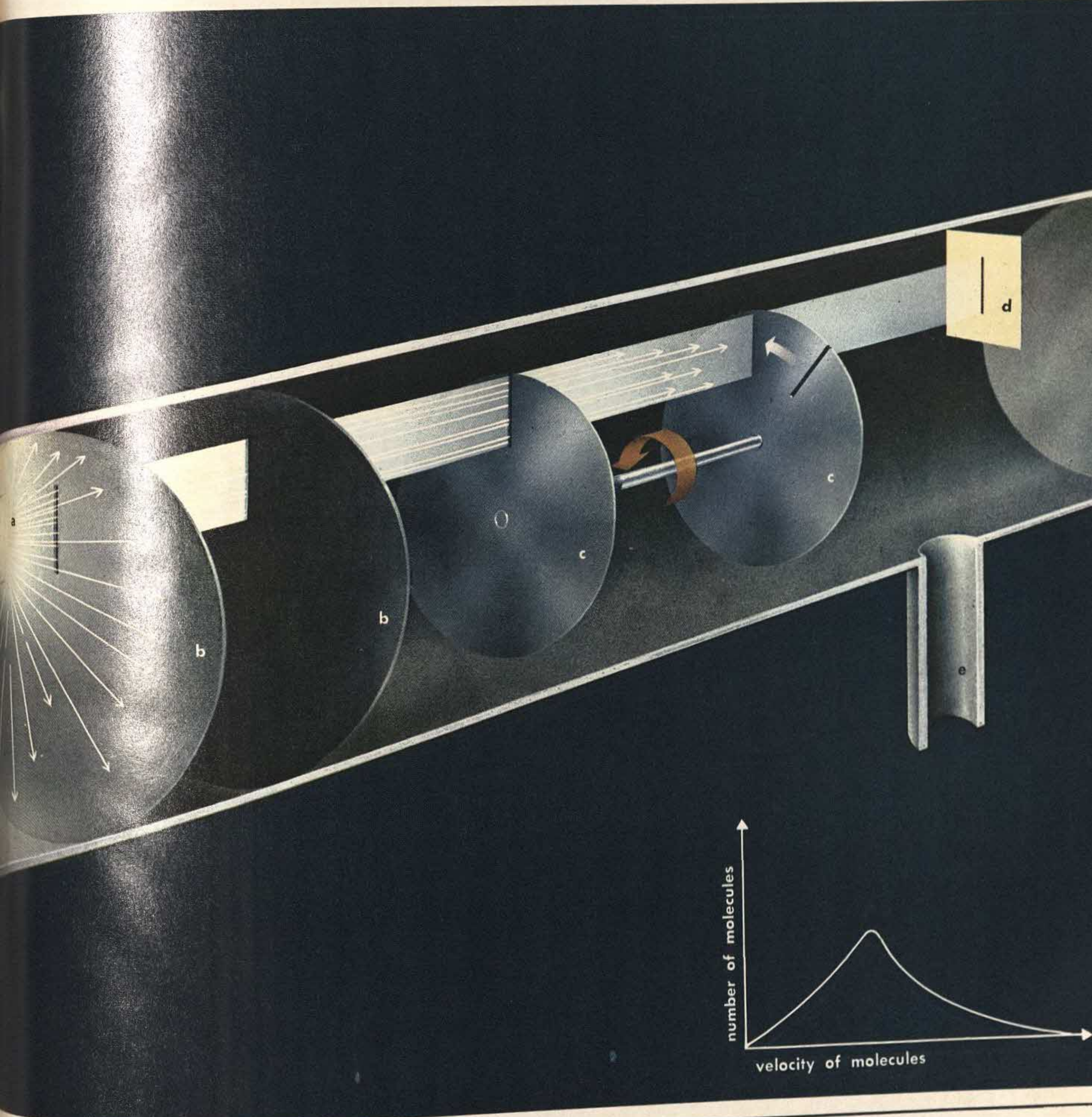
Two metal disks **b**, each with a radial slit, are mounted opposite each other in such a way that the two slits are aligned with the source of the molecules. The thin beam of molecules allowed to pass consists of only those molecules that are propagated along the axis containing the slits. These molecules, few in number compared to all the molecules escaping from the drop of silver, constitute the so-called molecular beam.

Two more metallic disks **c** are mounted opposite each other on the same rotating axis. Ordinarily they would obstruct the passage of the molecular ray; however, since each disk has a slit similar to the ones in **b**, the molecules can pass through at the slits. If the disks are rotated at a certain speed (by means of a motor and pulley), the only molecules that can pass through the disks will be those that have passed through the first slit and have enough speed to reach the second disk and its slit. Since the molecular ray contains molecules of many velocities (both less and greater than the average velocity), for each value of the velocity of rotation only some of the molecules will pass through both slits; the others will be stopped and deviated as they strike the walls of the disks. It now remains to be seen how many molecules travel at each particular velocity.

A glass plate **d** makes it possible to collect the molecules of silver that have passed through the selector. (In this case the molecules are monatomic.) The atoms stop on the glass and silver it; therefore, the degree of transparency of the glass measures the arrival frequency of the molecules.

The container in which the experiment is carried out is evacuated at **e** by mechanical and diffusion pumps. These pumps eliminate all the molecules of air, which permits the propagation of the silver atoms in a straight line, without molecular collisions.

The graph at lower right shows the velocity distribution of the molecules measured from the experiment. All values are possible ranging from very low velocities, almost zero, to exceedingly high velocities. The high velocities are rare, but they do exist; in the gas there is a nonnegligible percentage of molecules with velocities as much as five to ten times the average velocity, as the graph shows.



ABBREVIATIONS

A	ampere
Å	Ångstrom unit
abs	absolute
a-c	alternating current (as an adjective)
amu	atomic mass unit
atm	atmosphere
at. wt	atomic weight
AU	astronomical unit
avdp	avoirdupois
Bev	one billion electron volts
bhp	brake horsepower
bhp-hr	brake horsepower-hour
bp	boiling point
Btu	British thermal unit
C	temperature Celsius; temperature Centigrade
c	candle
cal	calorie
cfm	cubic feet per minute
cfs	cubic feet per second
cgs	centimeter-gram-second (system)
cl	centiliter
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
coef	coefficient
colog	cologarithm
cos	cosine
cot	cotangent
cp	candlepower
csc	cosecant
cu	cubic
cu ft	cubic foot
db	decibel
d-c	direct current (as an adjective)
doz	dozen
E	electromotive force
e	the base of the system of natural logarithms
ev	electron volt
F	temperature Fahrenheit
fp	freezing point
fpm	feet per minute
fps	feet per second
ft	foot; feet
ft^2	square foot
ft^3	cubic foot

ft-c	footcandle
ft-lb	foot-pound
G	universal gravitational constant
g	gram
gal	gallon
g-cal	gram-calorie
gpm	gallons per minute
gps	gallons per second
hr	hour
hν	photon energy
hp	horsepower
Hz	hertz (cycles per second)
I	electric current
ID	inside diameter
in.	inch
in.^{2}	square inch
in.^{3}	cubic inch
in.-lb	inch-pound
ips	inches per second
j	joule
K	temperature Kelvin (absolute)
kcal	kilocalorie
kg	kilogram
kg-cal	kilogram-calorie
kg-m	kilogram-meter
kg/m^3	kilograms per cubic meter
kgps	kilograms per second
km	kilometer
kv	kilovolt
kw	kilowatt
kwhr	kilowatt-hour
l	liter; lumen
lat	latitude
lb	pound
lb-ft	pound-foot
lb/ft^2	pounds per square foot
lb/ft^3	pounds per cubic foot
lb-in.	pound-inch
l-hr	lumen-hour
lin ft	linear foot
log	logarithm (common)
log$_e$	logarithm (natural)
long.	longitude
m	meter; minute (time, in astronomical circles)

m^2	square meter
m^3	cubic meter
ma	milliampere
Mev	one million electron volts
mg	milligram
mh	millihenry
mi	mile
mi^2	square mile
min	minute
m-kg	meter-kilogram
ml	milliliter
mm	millimeter
mm^2	square millimeter
mm^3	cubic millimeter
mμ	millimicron
mph	miles per hour
mphps	miles per hour per second
mv	millivolt
N	Avogadro's constant
n!	factorial *n*
OD	outside diameter
oz	ounce
pH	rating on acid-alkaline scale
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
R	temperature Reaumur; resistance
RA	right ascension
rpm	revolutions per minute
rps	revolutions per second
sec	secant; second
sin	sine
sp gr	specific gravity
sq	square
tan	tangent
V	volt
VA	volt-ampere
W	watt; work
yd	yard
yd^2	square yard
yd^3	cubic yard

SCIENTIFIC SYMBOLS AND ABBREVIATIONS

α	alpha particle
β; β^-	beta particle
β^+	positron
γ	gamma radiation
Δ	a small change; heat
λ	wavelength; radioactive-decay constant
ma	milliampere
μc	microcurie
μf	microfarad
μin.	microinch
μm	micron
$\mu\mu$	micromicron
$\mu\mu$f	micromicrofarad
ν	frequency; neutrino
π	3.14159; osmotic pressure

Σ	the sum of
σ	nuclear cross section (barns); area
Ω	electrical resistance (ohms)
ω	angular speed; angular velocity
$'$	minute (angular measure)
$''$	second (angular measure)
♂	male
♀	female
$>$	is greater than
$<$	is less than
$\propto$	is proportional to
∞	infinity
$\sqrt{}$	square root of
$^\circ$	degrees; temperature; angle measurement (example, 30°)

[ ]	molar concentration
$+$	positive electric charge; mixed with; plus
$-$	negative electric charge; single covalent bond; minus
$=$	equals; double covalent bond; produces
$\neq$	does not equal
$\equiv$	triple covalent bond
$\rightarrow$	produces; forms; chemical reaction
$\rightleftarrows$	reversible chemical reaction
$\uparrow$	gas produced by a chemical reaction
$\downarrow$	precipitate produced by a chemical reaction
*	radioactive substance (follows symbol of element; example, Cl*)

THE ILLUSTRATED SCIENCE DICTIONARY

Nicotinic Acid to Partial Pressure

KEY TO PRONUNCIATION

The diacritical marks are:

ə	b*a*nan*a*, *a*but
ᵊ	preceding l, m, n as in batt*le*
ə̇	*e*lectric
ər	f*ur*ther
a	m*a*t
ā	d*ay*
ä	c*o*t, f*a*ther
au̇	n*ow*, *ou*t
e	b*e*t
ē	b*ea*t
i	t*i*p
ī	b*i*te
j	*j*ob, *g*em
ŋ	si*ng*
ō	b*o*ne
ȯ	s*aw*, *a*ll
ȯi	c*oi*n
th	*th*in
t͟h	*th*en
ü	r*u*le, f*oo*l
u̇	p*u*ll, w*oo*d
ue	German h*ü*bsch
u̅e̅	French r*ue*
yü	*u*nion
zh	vi*si*on

ˈ mark preceding the syllable with strongest stress.

ˌ mark preceding a syllable with secondary stress.

The system of indicating pronunciation in these volumes is used by permission from Webster's *Third New International Dictionary*, copyright 1961 by G. & C. Merriam Co., Publishers of the Merriam-Webster Dictionaries.

nicotinic acid \\ˌnik-ə-ˈtē-nik ˈas-əd\\

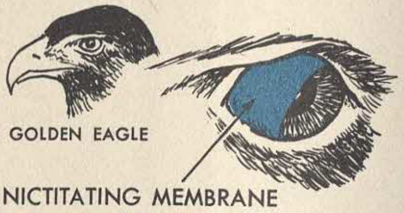
BIOLOGY and MEDICINE. An organic acid that is part of the vitamin B complex. It occurs in meat, fish, milk, grains and yeast and can be made synthetically by the partial oxidation of nicotine; sometimes called niacin.

Adequate NICOTINIC ACID *in the diet prevents pellagra.*

nictitating membrane \\ˈnik-tə-ˌtāt-iŋ ˈmem-ˌbrān\\

ZOOLOGY. A thin, movable membrane, or third eyelid, hinged at the inner side, or beneath the lower lid, of the eye of reptiles, birds and certain mammals. It is usually semiopaque.

A remnant of the NICTITATING MEMBRANE *is present in the inner corner of the human eye.*



nimbostratus \\ˌnim-(ˌ)bō-ˈstrāt-əs\\ *adj.*

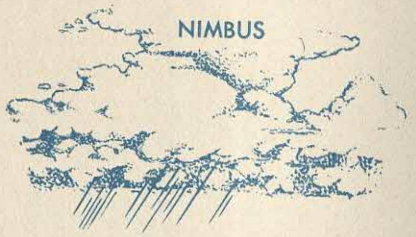
EARTH SCIENCE. Referring to a dark-gray, layered cloud that usually occurs at altitudes of less than 6,500 feet and that frequently produces rain or snow.

The bottom of a NIMBOSTRATUS *cloud may be irregular because rain falling from it evaporates before reaching the earth.*

nimbus \\ˈnim-bəs\\ *adj.*

EARTH SCIENCE. Referring to any of the clouds that produce, or are likely to produce, precipitation.

NIMBUS *clouds evolve from other clouds.*



nitrate \\ˈnī-ˌtrāt\\ *n.*

CHEMISTRY. Any compound that contains the nitrate group NO_3^{-1}; also, a salt or ester prepared from nitric acid and soluble in water.

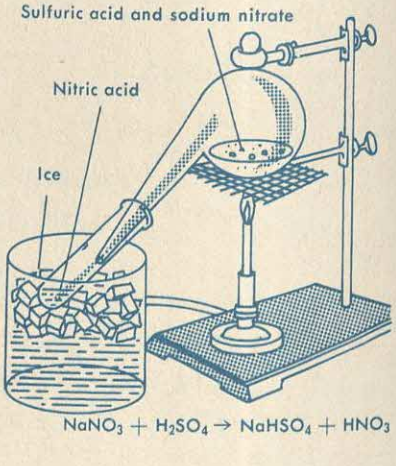
Potassium NITRATE *is widely used as a fertilizer.*

nitration \\nī-ˈtrā-shən\\ *n.*

CHEMISTRY. Any chemical reaction that causes the nitro (NO_2^-) group to become attached to a carbon atom in an organic molecule; usually, a replacement reaction in which one or more nitro groups replace one or more hydrogen atoms in a molecule, usually by reaction with nitric acid.

NITRATION *of benzene produces nitrobenzene that can be converted to aniline, the starting point for the chemical synthesis of many dyes.*

NITRIC ACID
(PREPARED IN LABORATORY)



$NaNO_3 + H_2SO_4 \rightarrow NaHSO_4 + HNO_3$

nitric acid \\ˈnī-trik ˈas-əd\\

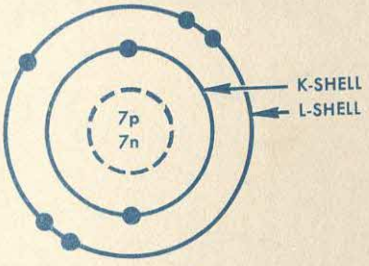
CHEMISTRY. A very strong acid and a powerful oxidizing agent; a water solution of hydrogen nitrate, HNO_3, that often has a yellow-brown color due to the formation of nitrogen tetroxide by decomposition.

NITRIC ACID *is used in making chemicals, dyes, explosives and fertilizers.*

nitrification \\ˌnī-trə-fə-ˈkā-shən\\ *n.*

BIOLOGY, CHEMISTRY and EARTH SCIENCE. A process in the nitrogen cycle that results in the conversion of ammonia to nitrates and of nitrites to nitrates.

NITRIFICATION *results mainly from the action of nitrifying bacteria.*



NITROGEN
(ATOM)

nitrogen \\ˈnī-trə-jən\\ *n.*

BIOLOGY and CHEMISTRY. A gaseous element that makes up about 78 percent of the earth's atmosphere. It is colorless, odorless and tasteless and does not react at ordinary temperatures and pressures. It is found in many reactive compounds, such as nitric acid, HNO_3, and ammonia, NH_3. Symbol, N; atomic number, 7; atomic weight, 14.0067.

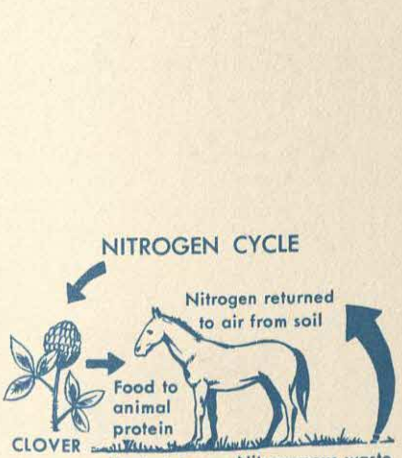
NITROGEN *occurs in protein compounds that are found in all living organisms.*

nitrogen cycle \\ˈnī-trə-jən ˈsī-kəl\\

BIOLOGY, CHEMISTRY and EARTH SCIENCE. A continuous series of events: Atmospheric nitrogen is changed into nitrogen compounds by bacteria and, to some extent, by lightning. These compounds are used in the production of amino acids by plants and in the synthesis of proteins by plants and animals. Upon the death of a plant or animal, the protein is converted to amino acids and ammonia by decay processes. The ammonia is then oxidized to nitrates and nitrites by nitrification, and the nitrates become available to plants again, or, along with the nitrites, are reduced to gaseous nitrogen and released into the atmosphere to complete the cycle.

The NITROGEN CYCLE, *like the carbon cycle, requires radiant energy from the sun in order to provide all organisms continuously with usable matter.*

NITROGEN CYCLE


Nitrogen returned to air from soil
Food to animal protein
CLOVER
Bacterial action
Nitrogenous waste from animals in soil

nitrogen fixation \\ˈnī-trə-jən fik-ˈsā-shən\\

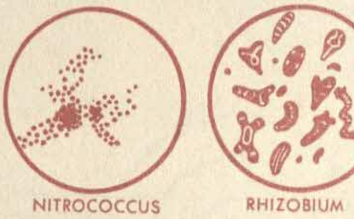
BIOLOGY, CHEMISTRY and EARTH SCIENCE. Any one of several chemical processes by which nitrogen from the atmosphere is combined with another element, or elements, to form a compound that will dissolve in water.

NITROGEN FIXATION *is used industrially to form ammonia.*

nitrogen-fixing bacteria \'nī-trə-jən 'fik-siŋ bak-'tir-ē-ə\
BIOLOGY, CHEMISTRY and EARTH SCIENCE. Bacteria living in soil or in nodules on the roots of plants, such as peas, beans or alfalfa, that utilize free atmosphere nitrogen in the synthesis of amino acids and proteins that, in turn, may be used by green plants.

NITROGEN-FIXING BACTERIA *are the only organisms that utilize atmospheric nitrogen naturally.*

NITROGEN-FIXING BACTERIA

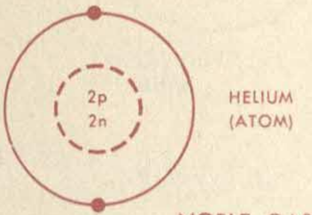


nitrogenous \nī-'träj-ə-nəs\ *adj.*
BIOLOGY and CHEMISTRY. Referring to a chemical compound that contains nitrogen.

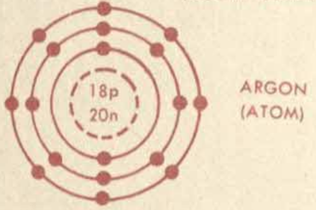
There are NITROGENOUS *proteins in all plant and animal substances.*

nitroglycerin \ˌnī-trō-'glis-(ə-)rən\ *n.*
CHEMISTRY. A colorless, oily liquid that is extremely unstable and explodes violently when subjected to shock or high temperature; a compound of carbon, hydrogen, oxygen and nitrogen.

Dynamite is made by soaking wood pulp in NITROGYLCERIN, *along with other substances, and then pressing the pulp into sticks.*



NOBLE GASES
(used in laboratory)

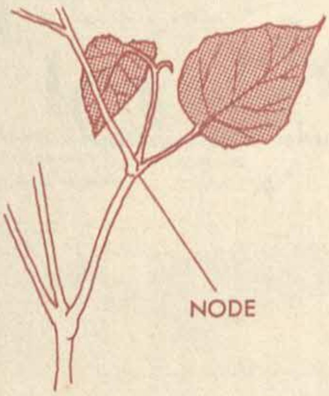


noble gases \'nō-bəl 'gas-əz\
CHEMISTRY. The gaseous elements helium, neon, argon, krypton, xenon and radon that are chemically nonreactive except under unusual conditions of temperature, pressure and excitation. Also called rare gases, although all occur in the atmosphere, they make up one group of the periodic table; see *periodic table*, p. 620.

The NOBLE GASES, *especially helium and argon, are used in some industrial or laboratory processes in which the heating of a given substance requires a nonreactive atmosphere.*

nocturnal \näk-'tərn-ᵊl\ *adj.*
BIOLOGY. Descriptive of an organism that is active, or of a function of an organism carried out, during the night, as contrasted with diurnal.

NOCTURNAL *animals often have eyes with large pupils.*



node \'nōd\ *n.*
1. ANATOMY, MEDICINE and ZOOLOGY. A small lump or swelling, either normal or caused by infection. 2. BOTANY. A joint between two segments, or internodes, in the stem of a plant; also, the portion of a stem to which the leaf is attached. 3. PHYSICS. In a

vibrating object (as a string), a point, line or other part that has very little, or no, vibratory motion. 4. ASTRONOMY. Either of two points where the orbit of a celestial body appears to intersect another orbit or plane, such as the ecliptic.

A lymph NODE *may swell if it becomes infected in the process of filtering lymphatic fluid.*

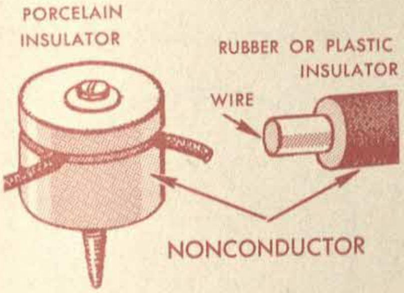
NODULE

nodule \ˈnäj-(ˌ)ü(ə)l\ *n.*
1. EARTH SCIENCE. A small lump or mass, found in a variety of sedimentary rocks, that differs in makeup from the main rock and apparently was formed after the rock was deposited; a small concretion. 2. BOTANY. Any small, knoblike growth on the stem or other parts of a plant, such as growths on the roots of legumes caused by nitrogen-fixing bacteria.

Flint commonly occurs as a NODULE *in chalk, limestone and dolomite.*

nonagon \ˈnō-nə-ˌgän\ *n.*
MATHEMATICS. A polygon having nine sides.

Each central angle of a regular NONAGON *is equal to 40 degrees.*

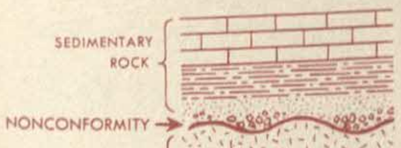


nonconductor \ˌnän-kən-ˈdək-tər\ *n.*
PHYSICS. A substance that does not readily transmit such energies as heat, electricity or sound; also called insulator.

Rubber, a NONCONDUCTOR, *is used as electric insulation.*

nonconformity \ˌnän-kən-ˈfȯr-mət-ē\ *n.*
EARTH SCIENCE. A surface, usually irregular, between a younger sedimentary rock layer and an older mass of igneous or metamorphic rocks; see *unconformity.*

A NONCONFORMITY *represents a period of time during which erosion took place or no sediments were deposited.*



NONCONFORMITY

nondisjunction \ˌnän-dis-ˈjəŋ(k)-shən\ *n.*
BIOLOGY. The failure of two chromosomes to separate during the reduction division of cells.

NONDISJUNCTION *influences the characteristics which will be inherited by an organism.*

nonmetals \(ˈ)nän-ˈmet-ᵊlz\ *n.*
CHEMISTRY. Chemical elements that are not good conductors of electricity and heat. Nonmetals tend to gain electrons in chemical reactions and thereby form negative ions. They are re-

garded as acid-forming elements, as contrasted with base-forming elements (metals).

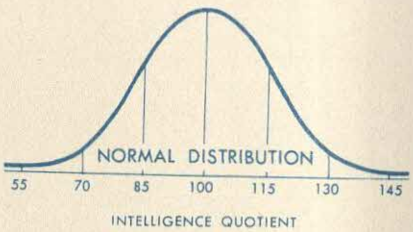
Oxygen (a gas), carbon (a solid) and bromine (a liquid) are all NONMETALS.

norm \'nȯ(ə)rm\ *n.*

MATHEMATICS. An arithmetical average, or mean; also, in calculus, the length of the longest segment into which an interval is divided, or partitioned.

The NORM *of the scores of high-school freshmen on a vocabulary test is above the norm for a similar eighth-grade group.*

NORMAL DISTRIBUTION



normal \'nȯr-məl\

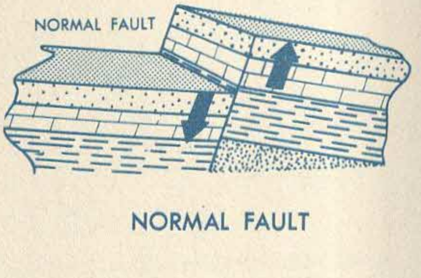
1. MATHEMATICS (N.). The line perpendicular to the line tangent to a curve or to the plane tangent to a curved surface at a given point. 2. CHEMISTRY (N.). A compound composed of molecules that contain a continuous chain of carbon atoms and that has its functional group attached to one end of the carbon chain rather than somewhere in the middle. (Adj.). Also, referring to the concentration of certain solutions; see *normal solution.*

If m is the slope of the tangent to a curve at a given point, then the slope of the NORMAL *to the curve is —1/m.*

normal distribution \'nȯr-məl ˌdis-trə-'byü-shən\

MATHEMATICS. A statistical distribution or function that, when represented graphically, appears as a symmetrical, bell-shaped curve.

A graph representing a random sampling of children's heights throughout the United States would graphically approximate a NORMAL DISTRIBUTION *curve.*



NORMAL FAULT

normal fault \'nȯr-məl 'fȯlt\

EARTH SCIENCE. A fracture in rock layers in which the hanging wall has apparently slipped down in relation to the footwall; also called gravity fault.

A NORMAL FAULT *results from tension on, or lengthening of, a segment of the earth's crust.*

normal salt \'nȯr-məl 'sȯlt\

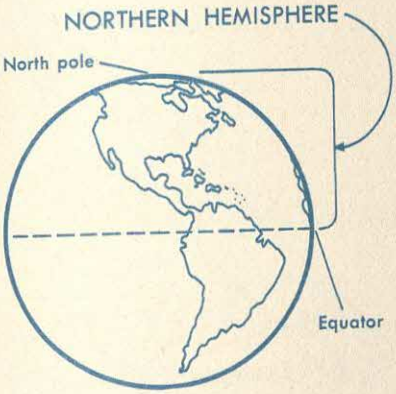
CHEMISTRY. A salt formed when all the hydrogen atoms of an acid molecule have been replaced by other positive ions.

Trisodium phosphate, Na_3PO_4, *is a* NORMAL SALT.

normal solution \'nȯr-məl sə-'lü-shən\

CHEMISTRY. For an acid, a solution that contains 1 mole, or 1 gram, of replaceable hydrogen atoms in 1,000 milliliters of solution; for a base, a solution that contains 1 mole, or 17 grams, of replaceable hydroxyl (OH) groups in 1,000 milliliters of solution; see *mole.*

Ten milliliters of a NORMAL SOLUTION *of acid will exactly neutralize 10 milliliters of a normal solution of base.*



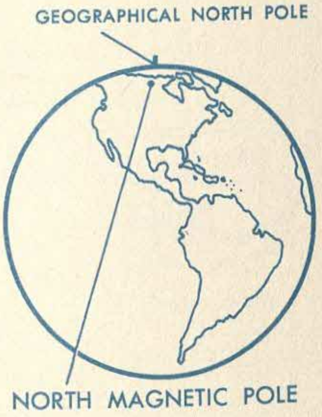
Northern Hemisphere \'nȯr-t͟hə(r)n 'hem-ə-ˌsfi(ə)r\

EARTH SCIENCE. The half of the earth that is north of the equator.

More of the earth's land area is located in the NORTHERN HEMISPHERE *than in the Southern Hemisphere.*

northern lights \'nȯr-t͟hə(r)n 'līts\

ASTRONOMY. A popular name for the aurora borealis. See *aurora borealis.*



north magnetic pole \'nȯ(ə)rth mag-'net-ik 'pōl\

EARTH SCIENCE. The place on the earth's surface toward which the north-seeking pole of a compass points. It is located near 72 degrees north latitude and 96 degrees west longitude.

At the NORTH MAGNETIC POLE, *a dipping needle will point straight up and down.*

North Pole \'nȯ(ə)rth 'pōl\

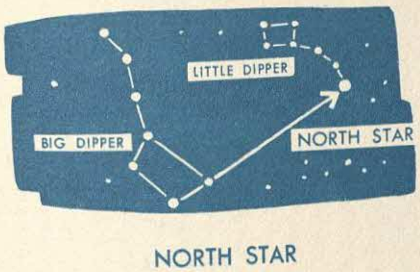
EARTH SCIENCE. The most northern point on the earth's surface. It is one of two points through which the imaginary line forming the earth's axis passes. It is also called the geographical north pole to distinguish it from the north magnetic pole.

There is no longitude designation for the NORTH POLE *because all meridians pass through it.*

north-seeking pole \'nȯ(ə)rth 'sēk-iŋ 'pōl\

PHYSICS. The end of a magnetized bar, such as a compass needle, that points north; often designated as N-pole.

The NORTH-SEEKING POLE *of any freely-suspended bar magnet will point toward the north magnetic pole.*



NORTH STAR

North Star \'nȯ(ə)rth 'stär\

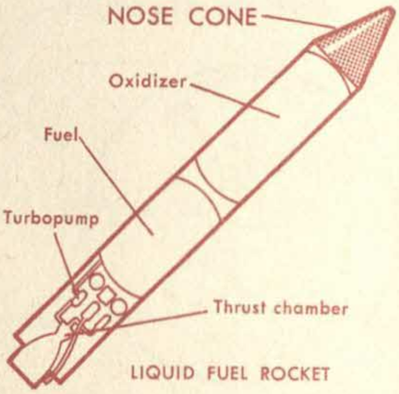
ASTRONOMY. A fairly-bright star located almost directly above the North Pole; Polaris.

At the equator, the NORTH STAR *is seen on the horizon.*

nose cone \'nōz 'kōn\

ASTRONAUTICS. The leading end of a rocket, built to withstand the high temperatures caused by friction in the atmosphere.

A NOSE CONE *is usually made of ablative materials.*



LIQUID FUEL ROCKET

nostrils \'näs-trəlz\ *n.*

ANATOMY and ZOOLOGY. The external openings of the nose; also called nares.

The NOSTRILS *of a seal are closed by a valvelike flap when it is under water.*

notochord \'nōt-ə-ˌkȯ(ə)rd\ *n.*

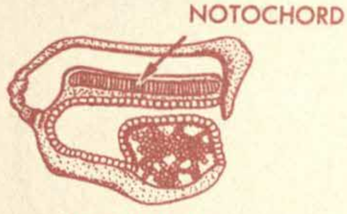
ZOOLOGY. An internal, elastic rod of cells that forms the supporting axis of the body of a chordate (an animal with a backbone type of skeleton) at some time during its life.

In vertebrates, the NOTOCHORD *appears only in the embryo and is later replaced by a vertebral column.*

nova \'nō-və\ *n.*

ASTRONOMY. A faint star that rapidly becomes much brighter, sometimes 10,000 times more intense, and then grows dim again or fades to invisibility over a period of months or years; see *supernova.*

According to present theories of stellar evolution, a NOVA *is a star that will eventually become a white dwarf.*



FROG EMBRYO

N-shell \'en-ˌshel\ *n.*

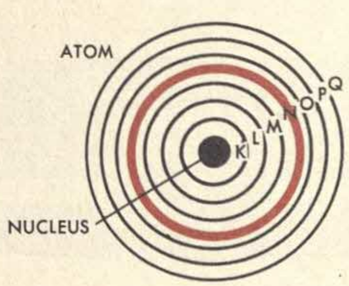
CHEMISTRY and PHYSICS. One of the seven principal energy levels, identified by the letters K, L, M, N, O, P and Q, that electrons may occupy in an atom; the fourth principal energy level that electrons may occupy in the Bohr model for the atom.

An electron in the N-SHELL *may absorb energy and jump to the O-shell, or lose energy and drop to the M-shell if space is available.*

nth \'enth\ *adj.*

MATHEMATICS. Pertaining to any number or quantity denoted by n; also, the ordinal number associated with n.

If the NTH *power of 2 is 16, then n is equal to 4 because* $2^4 = 16$.



N-SHELL

nuclear chemistry \'n(y)ü-klē-ər 'kem-ə-strē\

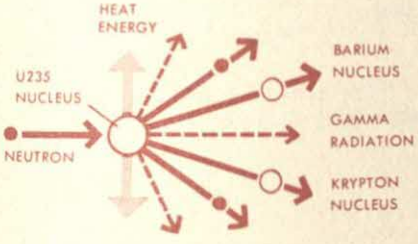
CHEMISTRY. The study of chemical reactions involving combination of atomic nuclei and transmutation of isotopes; also, the chemical procedures used in separating uranium, fission products and other radioactive substances from various materials.

NUCLEAR CHEMISTRY *has made it possible to obtain useful radioactive elements from the fission products of uranium.*

nuclear energy \'n(y)ü-klē-ər 'en-ər-jē\

PHYSICS. The energy produced by reactions involving combination of split (fission) or in which two atomic nuclei join to make one nucleus (fusion). Such energy may be in the form of heat, light or other radiation and is distinguished from chemical energy, which is not produced as a result of reacting nuclei.

The energy received by the earth from the sun is NUCLEAR ENERGY.



NUCLEAR FISSION

nuclear equation \'n(y)ü-klē-ər i-'kwā-zhən\

CHEMISTRY and PHYSICS. A symbolic expression, or equation, that describes the kind and number of atomic nuclei before and after a nuclear reaction. It also shows the kind and number of subatomic particles or kind of radiation absorbed or emitted by the reaction.

The neutron was discovered by the reaction between an alpha particle (helium nucleus) and a beryllium nucleus that produces a carbon nucleus and a free neutron and is expressed by the following NUCLEAR EQUATION: ${}_2He^4 + {}_4Be^9 \rightarrow {}_6C^{12} + {}_0n^1$.

nuclear fission \'n(y)ü-klē-ər 'fish-ən\

PHYSICS. The division of an atomic nucleus into parts of approximately-equal mass. This division may be produced naturally, by spontaneous fission, or artificially, as a result of bombardment with neutrons.

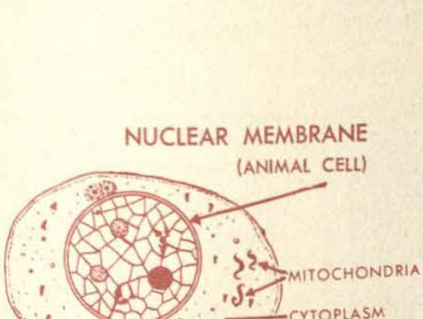
Energy released by an atomic bomb is produced by the NUCLEAR FISSION *of heavy atoms, such as those of uranium or plutonium.*

nuclear fusion \'n(y)ü-klē-ər 'fyü-zhən\

PHYSICS. A nuclear reaction in which light atomic nuclei unite to form heavier nuclei, releasing large amounts of energy.

The energy produced by the sun is the result of NUCLEAR FUSION *in which hydrogen is converted to helium.*

NUCLEAR MEMBRANE
(ANIMAL CELL)



nuclear membrane \'n(y)ü-klē-ər 'mem-ˌbrān\

BIOLOGY. A living double membrane composed of proteins and fatty substances. It encloses the nucleus of a cell and apparently controls the traffic of materials between nucleus and cytoplasm.

During mitosis, the NUCLEAR MEMBRANE *breaks down, enabling chromosome pairs to move to opposite poles of the dividing cell.*

nuclear physics \'n(y)ü-klē-ər 'fiz-iks\

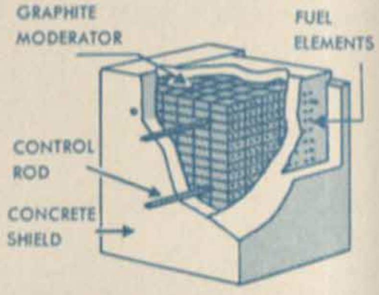
PHYSICS. The study of atomic nuclei, subatomic particles, nuclear reactions and the energy produced by the reactions; see *nuclear chemistry.*

One goal of NUCLEAR PHYSICS *is to develop a model that can be used to explain all nuclear reactions.*

nuclear reactor \'n(y)ü-klē-ər rē-'ak-tər\

PHYSICS. A device, used as a source of power, in which nuclear fission is sustained and controlled; also called atomic pile and atomic furnace.

The NUCLEAR REACTOR *may eventually become a common source of electric power.*



NUCLEAR REACTOR

nuclear rocket \'n(y)ü-klē-ər 'räk-ət\

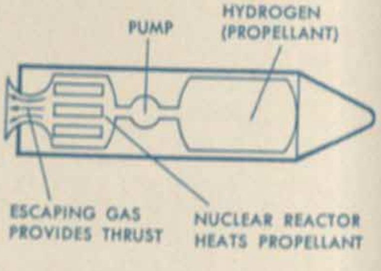
ASTRONAUTICS. A reaction-type power plant that uses an atomic reactor to heat a gas to high temperatures. It then expels the gas through a nozzle; also, theoretically, a reaction-type engine that uses the particles and energy released by atomic fission or fusion to provide thrust.

A NUCLEAR ROCKET *is more economical in its use of fuel than a chemical rocket.*

nucleic acid \n(y)u̇-'klē-ik 'as-əd\

BIOLOGY and CHEMISTRY. A complex compound, weakly acidic, found in all living cells. Composed of carbon, hydrogen, oxygen, nitrogen and phosphorus, it is thought to control the cell's growth in combination with proteins. It may be either ribonucleic acid (RNA) or deoxyribonucleic acid (DNA), and it usually occurs in combination with proteins; see *deoxyribonucleic acid* and *ribonucleic acid.*

Deoxyribonucleic acid is a NUCLEIC ACID *found in the nuclei of all living cells, and it may be the chemical transmitter of hereditary characteristics.*


PUMP
HYDROGEN (PROPELLANT)
ESCAPING GAS PROVIDES THRUST
NUCLEAR REACTOR HEATS PROPELLANT

NUCLEAR ROCKET

nucleolus \n(y)ü-'klē-ə-ləs\ *n.*

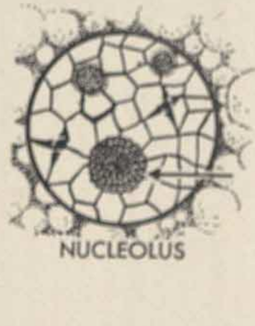
BIOLOGY. A spherical body found in the nuclei of cells not undergoing cell division and believed to be involved in the control of protein synthesis within cells.

A nucleus usually contains one NUCLEOLUS, *although, in certain cell types, there may be two or more.*

nucleonics \,n(y)ü-klē-'än-iks\ *n.*

PHYSICS. The study and science of nucleons or the behavior of the atomic nucleus, as in radioactivity, fission and fusion.

Geiger counters or scintillation counters are used in many research projects in NUCLEONICS.



NUCLEOLUS

nucleons \'n(y)ü-klē-,änz\ *n.*

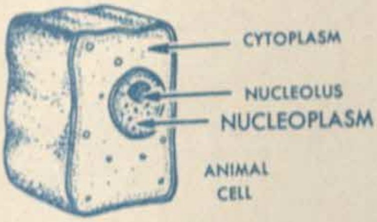
CHEMISTRY and PHYSICS. The protons and neutrons that make up the nucleus of any atom.

The total number of NUCLEONS *in an atom is the atomic mass for that particular atom.*

nucleoplasm \'n(y)ü-klē-ə-,plaz-əm\ *n.*

BIOLOGY. The protoplasm, or living matter, that makes up the nucleus of a cell; see *protoplasm* and *cytoplasm.*

The NUCLEOPLASM *is a gel-like substance in which chromosomes and nucleoli are suspended.*



nucleus \'n(y)ü-klē-əs\ *n.*

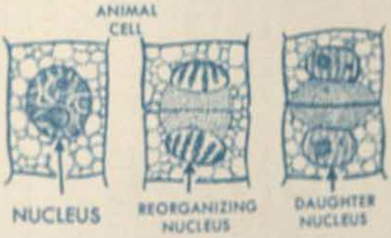
1. BIOLOGY. A dense, rounded body in the cytoplasm of most plant and animal cells, consisting of chromosomes and one or more nucleoli suspended in protein gel and surrounded by a membrane. It controls metabolism, growth and division of the cell. 2. CHEMISTRY and PHYSICS. The positively-charged core of an atom, composed of protons and neutrons. The nucleus makes up most of the mass of the atom but takes up only a small part of its volume. 3. ASTRONOMY. A dense, bright core, as of a comet or galaxy.

Striated muscle cells contain more than one NUCLEUS, *while short-lived red blood corpuscles in human beings contain no nucleus.*

nuclide \'n(y)ü-,klīd\ *n.*

CHEMISTRY and PHYSICS. A specific kind of atom whose nucleus is composed of a certain combination of protons and neutrons.

The NUCLIDE *carbon 14 is one of the dozen or so naturally-occurring radioactive nuclides.*



null set \'nəl 'set\

MATHEMATICS. An empty set, or a set that contains no elements, commonly denoted by the symbol ϕ.

The solution of the set of equations $x - y = 5$ *and* $2x - 2y = 5$ *is the* NULL SET.

number \'nəm-bər\ *n.*

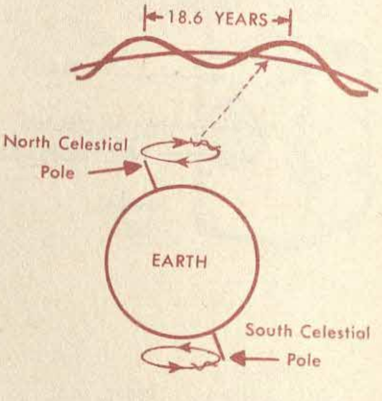
MATHEMATICS. A concept or idea used in expressing how many objects are in a given act; the property that two sets have in common when their elements can be matched in a one-to-one correspondence. From the foregoing elementary notions, the concept of number may be extended to represent a part, or portion, of an object or of a set of objects, a point on a line or the root of an equation.

A NUMBER *may be represented in many different ways, as by a numeral, by a spoken or written word or by a code.*

number scale \'nəm-bər 'skāl\

MATHEMATICS. A geometric representation of our real number system, determined by a straight line and two points on that line. One point, called zero, is the origin, and another point, called one, is usually placed to the right of zero, determining the unit of the scale. From these two points, every point of the whole line may be determined in such a way that corresponding to each point on the line there is a real number, called its coordinate, and corresponding to each real number there is a point on the line.

Understanding the use of a NUMBER SCALE *is basic to all types of graphical representation.*



NUTATION

numeral \'n(y)üm-(ə-)rəl\ *n.*
MATHEMATICS. The symbol used to represent a number, as an Arabic numeral or a Roman numeral.

The Arabic NUMERAL *32 can also be represented by the Roman numeral XXXII.*

numerator \'n(y)ü-mə-ˌrāt-ər\ *n.*
MATHEMATICS. That term of a fractional numeral, or symbol representing a fraction, written above the dividing bar, or line.

In the fraction ¾, the NUMERATOR *is 3.*

nutation \n(y)ü-'tā-shən\ *n.*
ASTRONOMY. A slight but regular change in the direction of the earth's axis, caused by the varying gravitational attraction of the sun and moon upon the earth; the nodding of the earth's axis as the axis slowly precesses. 2. BOTANY. Spiraling movement in the growth of certain plant parts, particularly stem tips and tendrils, due to unequal growth rates of cells.

The NUTATION, *or wavy motion in the precessional motion of the earth's axis, has a period of 18.6 years.*

NYMPH

GRASSHOPPER

nutrient \'n(y)ü-trē-ənt\ *n.*
BIOLOGY and PHYSIOLOGY. Any substance needed for the life and growth of an organism; a food.

Protein is a NUTRIENT *used by the human body to build and repair tissues.*

nymph \'nim(p)f\ *n.*
ZOOLOGY. An immature stage in the life cycle of an insect undergoing gradual metamorphosis.

A grasshopper NYMPH *resembles an adult in appearance and behavior.*

O

oasis \ō-'ā-səs\ *n.*

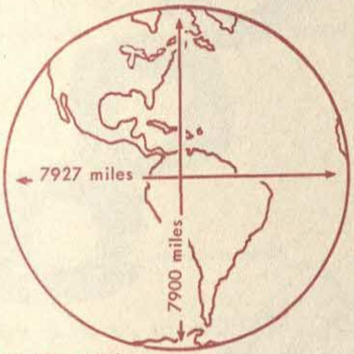
EARTH SCIENCE. A fertile area in a desert, characterized by a water supply, such as a natural spring, and usually by the presence of trees and other vegetation.

It is sometimes possible to create an OASIS *in the desert by means of irrigation.*

objective lens \əb-'jek-tiv 'lenz\

PHYSICS. In a microscope or telescope, the lens, or combination of lenses, closest to the object being viewed.

In a compound microscope, the OBJECTIVE LENS *may be used to produce different magnifications.*



OBLATENESS
DUE TO EARTH'S ROTATION

oblateness \äb-'lāt-nəs\ *n.*

ASTRONOMY. A flattening or depression of a spheroid at the poles.

The earth's OBLATENESS *is shown by the difference in its polar and equatorial diameters.*

oblique angle \ō-'blēk 'aŋ-gəl\

MATHEMATICS. Any angle that is not a right angle or a straight angle, as an acute, obtuse or reflex angle.

If one of the angles of a parallelogram is an OBLIQUE ANGLE, *then all its angles are oblique.*

OBSERVATORY

observatory \əb-'zər-və-ˌtōr-ē\ *n.*

1. ASTRONOMY. A building containing a telescope and other equipment necessary in the study of astronomical objects and phenomena. 2. EARTH SCIENCE. A building equipped for observing and recording meteorological, magnetic or seismological phenomena.

The largest optical telescope in the world is located in an OBSERVATORY *on Mount Palomar in California.*

obtuse angle \äb-'t(y)üs 'aŋ-gəl\

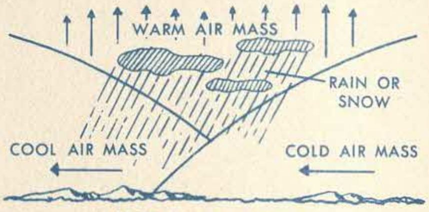
MATHEMATICS. An angle greater than a right angle and less than a straight angle.

A plane triangle can have only one OBTUSE ANGLE.

occluded front \ə-'klüd-əd 'frənt\

EARTH SCIENCE. The weather condition in which a cold front overtakes a warm front, and the edge of one front moves up over the edge of the other.

Rain or snow almost always accompanies an OCCLUDED FRONT.

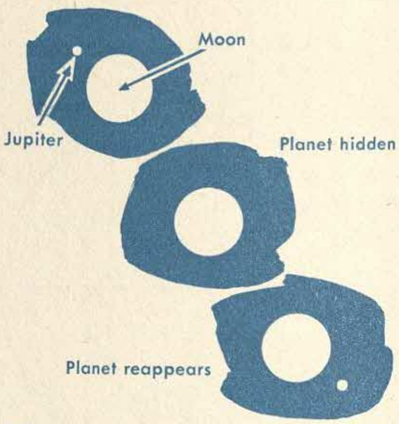


OCCLUDED FRONT

occultation \ˌäk-(ˌ)əl-'tā-shən\ *n.*

ASTRONOMY. The stoppage of light from one celestial body by an intervening body, as in the case of the moon passing in front of a star or planet, or a planet passing in front of a star or another planet; especially, an eclipse of a planet or a star by the moon.

The sudden disappearance and later reappearance of a star during OCCULTATION *is evidence that the moon's atmosphere is very thin.*



OCCULTATION (OF JUPITER BY MOON)

ocean \'ō-shən\ *n.*

EARTH SCIENCE. The large, continuous body of salt water that covers almost three fourths of the earth's surface; also, one of the five regions into which this ocean is divided: Atlantic, Pacific, Indian, Arctic and Antarctic.

The OCEAN *contains about 3½ percent salt by weight, most of which is sodium chloride, or common table salt.*

oceanography \ˌō-shə-'näg-rə-fē\ *n.*

EARTH SCIENCE. The study of the shape, content, behavior and effects of the ocean.

Research in OCEANOGRAPHY *has increased rapidly in the last few years.*

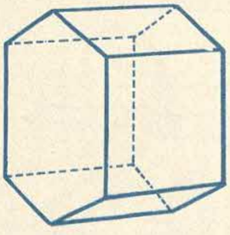
octagon \'äk-tə-ˌgän\ *n.*

MATHEMATICS. A polygon having eight sides.

A regular OCTAGON *is not often seen in nature.*

octahedron \ˌäk-tə-'hē-drən\ *n.*

MATHEMATICS. A polyhedron having eight faces.



OCTAHEDRON

In its natural state, a diamond crystal frequently has the shape of an OCTAHEDRON.

octane \'äk-ˌtān\ *n.*

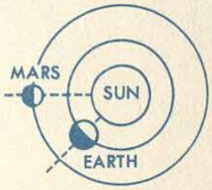
CHEMISTRY. C_8H_{18}. A colorless, flammable liquid that is one of the natural components of petroleum.

OCTANE *is one of several components in the hydrocarbon mixture called gasoline.*

octane rating scale \'äk-,tān 'rāt-iŋ 'skāl\

CHEMISTRY. A standard scale for rating the antiknock value of gasolines. On the scale, isooctane is rated 100 and normal heptane is rated 0. A given gasoline receives a number that corresponds to the percentage of isooctane mixed with normal heptane that will equal it in antiknock value. Thus, 90-octane gasoline is equal to a mixture that is 90 percent isooctane and 10 percent normal heptane.

The addition of small amounts of lead tetraethyl to a gasoline can raise the gasoline's value on the OCTANE RATING SCALE.



OCTANT

octant \'äk-tənt\ *n.*

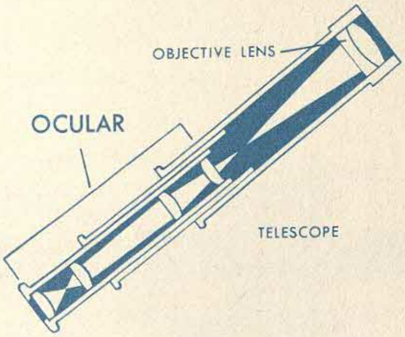
1. ASTRONOMY. The position of a celestial body when it is halfway between opposition or conjunction and quadrature; also, a device used to measure the altitudes of celestial bodies. 2. MATHEMATICS. An arc equal to ⅛ circle; also, one of the 8 partitions of a 3-dimensional space formed by the 3 perpendicular coordinate planes determined by the x-axis, the y-axis and the z-axis.

At its OCTANT, *the moon is either crescent or gibbous.*

octave \'äk-tiv\ *n.*

PHYSICS. An interval in the electromagnetic spectrum, comparable to a musical octave in which the frequencies at the beginning of the interval and at the end are in the ratio of 1:2; also, a similar relationship between two frequencies of sound.

The visible portion of the electromagnetic spectrum constitutes approximately one OCTAVE.



ocular \'äk-yə-lər\

1. ANATOMY and ZOOLOGY (Adj.). Referring to the eye or to its parts and functions. 2. (N.). The eyepiece of a telescope, microscope or other optical instrument.

OCULAR *muscles make rapid movements of the eye possible.*

odd parity \'äd 'par-ət-ē\

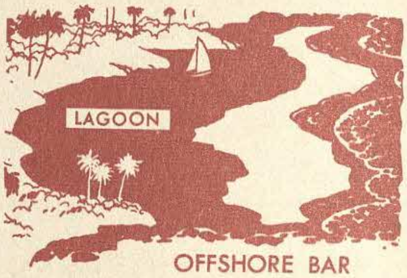
ENGINEERING and MATHEMATICS. A method of representing and interpreting computer data, where each valid character contains an odd number of binary digits in the "on" condition; see *even parity.*

When computer data is stored in ODD PARITY *on magnetic tape, one of the channels on the tape serves as a check to determine whether or not conditions of odd parity have been met on the other six channels.*

oersted \'ər-stəd\ *n.*

PHYSICS. The centimeter-gram-second electromagnetic unit of magnetic intensity equal to the intensity of a magnetic field in a vacuum in which a unit magnetic pole experiences a mechanical force of one dyne in the direction of the field; formerly called gauss.

The OERSTED *is named for Hans Christian Oersted, the Danish scientist who established the relationship between electricity and magnetism.*



OFFSHORE BAR

offshore bar \'ȯf-'shō(ə)r 'bär\

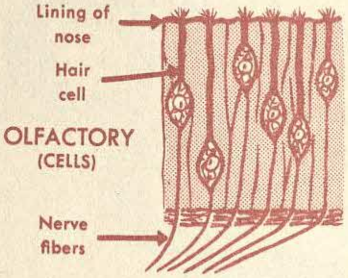
EARTH SCIENCE. A sand bar some distance from the shore and parallel to it; sometimes called a barrier beach.

Water between an OFFSHORE BAR *and a coastline is called a lagoon.*

ohm \'ōm\ *n.*

PHYSICS. A unit of measurement of resistance to a flow of electricity; specifically, the electrical resistance of 14.4521 grams of mercury at 0° C. in a tube 106.3 cm. long.

When a potential difference of one volt is applied across a resistance of one OHM, *one ampere of current flows.*



OLFACTORY (CELLS)

oil \'ȯil\ *n.*

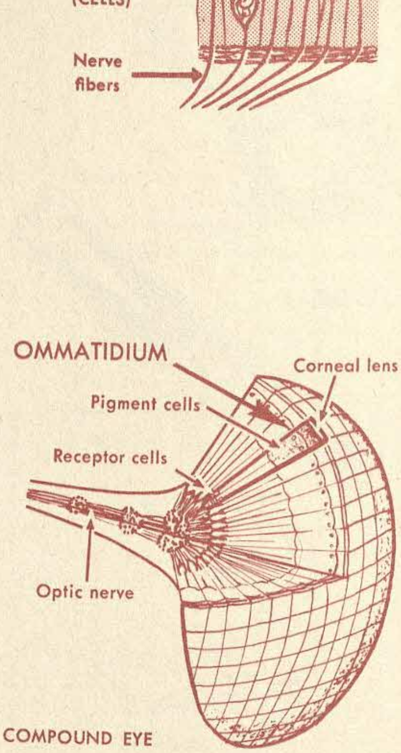
CHEMISTRY. Any one of several greasy or fatty liquids that is composed principally of hydrogen and carbon compounds, does not mix with water and may be obtained from petroleum or vegetable seeds. Oils are chemically similar to fats and waxes but have a lower melting point.

The corn or peanut OIL *used for cooking is obtained by pressing corn or peanut seeds.*

olfactory \äl-'fak-t(ə-)rē\ *adj.*

PHYSIOLOGY. Referring to the organs of smell or to the sense of smell.

In man, the OLFACTORY *nerve endings are located in the membranes of the nasal passage.*



COMPOUND EYE

ommatidium \ˌäm-ə-'tid-ē-əm\ *n.*

ZOOLOGY. One of the complete visual elements of the compound eye of an arthropod, containing an external corneal lens, pigment cells adjusting light intensity and receptor cells controlling nerve impulses.

Each OMMATIDIUM *in the compound eye of the locust responds to the light in its visual field.*

omnivorous \äm-'niv-(ə-)rəs\ *adj.*

ZOOLOGY. Descriptive of an animal that habitually eats both plant and animal foods.

The bear is an OMNIVOROUS *animal.*

OMNIVOROUS

ontogeny \än-'täj-ə-nē\ *n.*

BIOLOGY. All the phases in the development of an individual organism; see *phylogeny.*

The ONTOGENY *of human embryos appears to recreate the evolutionary history of the animal kingdom.*

oogenesis \ˌō-ə-'jen-ə-səs\ *n.*

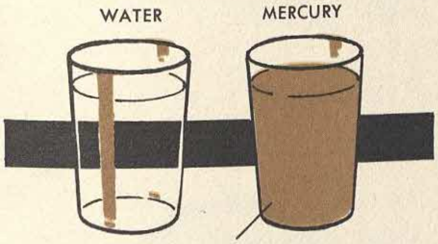
BIOLOGY. The process of egg formation, including the production of an ovum from special body cells by meiosis and mitosis and the preparation of the ovum for fertilization and development. Oogenesis is comparable with spermatogenesis in males.

During the OOGENESIS *of chicken eggs, considerable yolk is stored in the cytoplasm.*

opaque \ō-'pāk\ *adj.*

Referring to the property of a substance that does not transmit light; also, referring to a substance that is impervious to other forms of radiation besides visible light.

Limestone, wood and iron are OPAQUE *substances.*



OPAQUE

opalescence \ˌō-pə-'les-ᵊn(t)s\ *n.*

EARTH SCIENCE. The property of certain translucent minerals or gems that reflect an iridescent light or that have a milky iridescence.

The OPALESCENCE *of some minerals makes them highly prized as gems.*

open circuit \'ō-pən 'sər-kət\

PHYSICS. A loop, or path, made of a good electrical conductor that would carry an electric current except for a break or gap in the conductor.

An OPEN CIRCUIT *is the result when a light switch is turned to "off."*

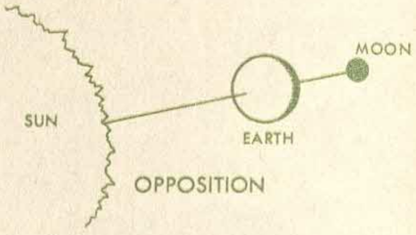
operant \'äp-ə-rənt\ *adj.*

Referring to something that is functioning effectively; also, referring to something that it is possible to observe and to measure.

Newton's laws of motion concerning gravity and inertia are OPERANT *throughout the solar system.*

operational definition \ˌäp-ə-ˈrā-shnəl ˌdef-ə-ˈnish-ən\
CHEMISTRY and PHYSICS. A description of a substance based on the observed properties and behavior of the substance.

Unlike the conceptual definition of a substance, an OPERATIONAL DEFINITION *is not concerned with the substance's composition and structure.*



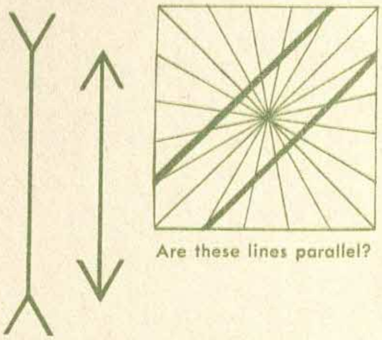
OPPOSITION

operculum \ō-ˈpər-kyə-ləm\ *n.*
1. ZOOLOGY. On bony fishes, the hinged plate on either side of the head that covers and protects the gills. 2. BOTANY. A lid or cover, such as the removable top of a spore capsule in mosses.

Fish whose skeletal parts consist of cartilage, such as sharks and skates, do not have an OPERCULUM.

ophthalmology \ˌäf-ˌthal-ˈmäl-ə-jē\ *n.*
MEDICINE. That branch of medicine concerned with the structure, functions and diseases of the eye.

OPHTHALMOLOGY *includes the diagnosis and medical treatment of eye diseases.*


Are these lines parallel?

Are these lines the same length?

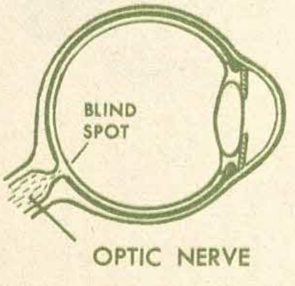
OPTICAL ILLUSION

opposition \ˌäp-ə-ˈzish-ən\ *n.*
ASTRONOMY. The situation that occurs when a celestial body is on the side of the earth away from the sun so that a straight line would pass through the sun, the earth and the celestial body in that order; also, the condition of any two celestial bodies located opposite each other on the celestial sphere, with a difference in longitude of 180 degrees.

The moon is full when it is in OPPOSITION.

optical illusion \ˈäp-ti-kəl il-ˈü-zhən\
A situation in which a person has certain experiences or impressions from what he sees that do not correspond to physical reality.

A motion picture can create the OPTICAL ILLUSION *that an object which changes position in a series of still pictures projected in rapid sequence is in motion.*



OPTIC NERVE

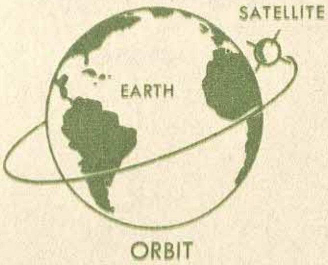
optic nerve \ˈäp-tik ˈnərv\
ANATOMY. The nerve that carries visual impulses from the retina of the eye to the brain.

The spot where the OPTIC NERVE *is attached to the retina is insensitive to light.*

optics \'äp-tiks\ *n.*

PHYSICS. The study of light and vision. Optics deals with the phenomena associated with electromagnetic radiation frequencies that fall between X rays and microwaves.

In OPTICS, *many laws that describe light phenomena hold true for infrared and ultraviolet radiations.*



optometry \äp-'täm-ə-trē\ *n.*

MEDICINE. The study and testing of the eyes for defects and the prescribing of corrective lenses.

The practice of OPTOMETRY *does not include medical treatment of eye diseases.*

oral \'ōr-əl\ *adj.*

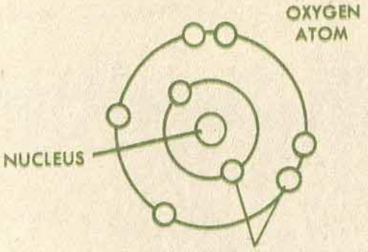
PHYSIOLOGY. Having to do with the mouth.

ORAL *hygiene is one means of preventing tooth decay.*

orbit \'ȯr-bət\ *n.*

1. ASTRONAUTICS and ASTRONOMY. The circular or elliptical path in which a celestial object or a space vehicle revolves around another body. 2. PHYSICS. The path of an electron around the nucleus of an atom. 3. ANATOMY. The eye socket.

Asteroids revolve around the sun between the ORBIT *of Mars and the orbit of Jupiter.*



orbital electron \'ȯr-bət-ᵊl i-'lek-ˌträn\

CHEMISTRY and PHYSICS. An electron that forms part of an atom and is located outside the nucleus. It occupies a particular energy level, or shell, in the Bohr model for the atom.

An ORBITAL ELECTRON *sometimes shifts to a higher energy level when an atom absorbs energy.*

orbital period \'ȯr-bət-ᵊl 'pir-ē-əd\

ASTRONAUTICS and ASTRONOMY. The time required for an orbiting body to complete one passage around the body it orbits; the time of one revolution.

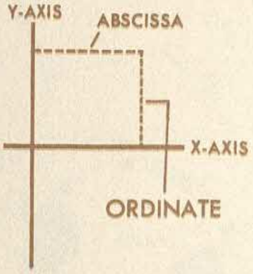
The ORBITAL PERIOD *of Sputnik I, the first artificial satellite, was 96.2 minutes.*

order \'ȯrd-ər\ *n.*

1. BIOLOGY. A category of plants or animals that are related. An order is a subdivision of a class and is further divided itself into suborders and families. 2. MATHEMATICS. The arrangement of quantities or terms in some specified manner; also, the

degree of a curve or of an equation; also, the number of rows or columns of a determinant.

Man belongs to the class Mammalia, the ORDER *Primates and the family Hominidae.*



ordered pair \'ȯrd-ərd 'pa(ə)r\

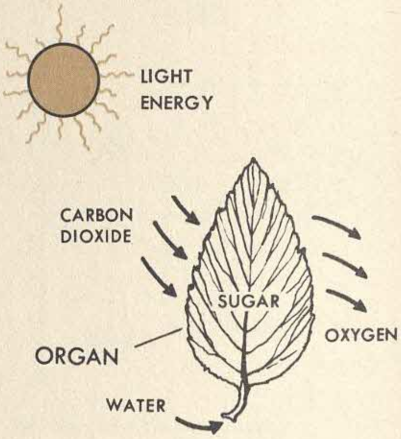
MATHEMATICS. A pair of numbers, usually enclosed in parentheses, described as ordered because the order in which they occur is important; for example, (x, y) is not generally equal to (y, x).

Because a rational number may be considered an ORDERED PAIR *of integers, (2/3) may be written (2, 3).*

ordinal number \'ȯrd-nəl 'nəm-bər\

MATHEMATICS. A number that designates position in an ordered sequence, as first, second or third.

The fifth page and the eighth of May are both expressions containing an ORDINAL NUMBER.



ordinate \'ȯrd-nət\ *n.*

MATHEMATICS. The signed number that represents the direction and the distance of a point from the x-axis of a Cartesian coordinate system.

The second number of an ordered pair of numbers denoting a point in a coordinate system is the ORDINATE *of the point.*

ore \'ō(ə)r\ *n.*

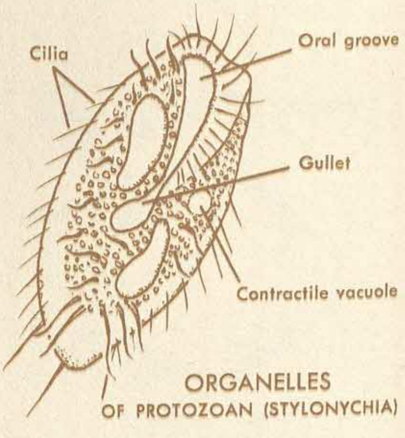
CHEMISTRY and EARTH SCIENCE. Any rock or natural mineral aggregate found in the earth's crust from which useful metals may be extracted.

Bauxite is an ORE *of aluminum.*

organ \'ȯr-gən\ *n.*

BIOLOGY. A group of cells or tissues that forms a part of a plant or animal and performs a specific function.

In plants, the leaf is a food-making ORGAN.

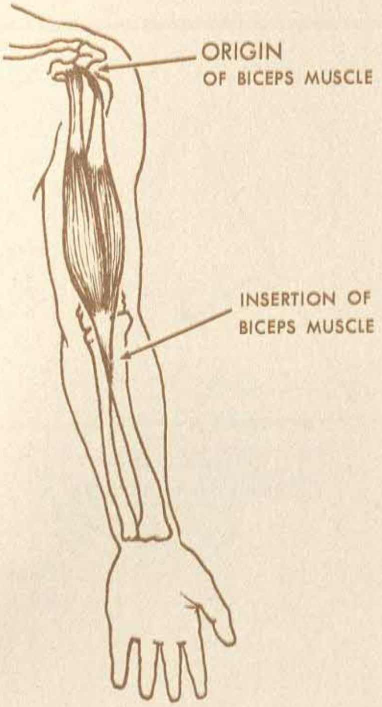


ORGANELLES
OF PROTOZOAN (STYLONYCHIA)

organelles \ˌȯr-gə-'nelz\ *n.*

ZOOLOGY. In one-celled organisms, small parts with special functions. They may be compared with organs in many-celled organisms.

Numerous ORGANELLES *called cilia enable some protozoans to move about.*



organic \ȯr-ˈgan-ik\ *adj.*

1. CHEMISTRY. Pertaining to a carbon compound or to something composed of carbon compounds. 2. BIOLOGY. Having, or composed of, organs; also, referring to organisms that are alive, or were once alive.

Gasoline, sugar and starch are some common ORGANIC *substances.*

organic acid \ȯr-ˈgan-ik ˈas-əd\

CHEMISTRY. Any one of a group of carbon compounds having a molecule that contains the carboxyl group (—COOH). Many organic acids are soluble in water and display the usual acid properties, such as sour taste and a *p*H value of less than seven. They are usually weaker in acid properties than inorganic acids.

The sour taste of vinegar is caused by the presence of acetic acid, an ORGANIC ACID.

organism \ˈȯr-gə-ˌniz-əm\ *n.*

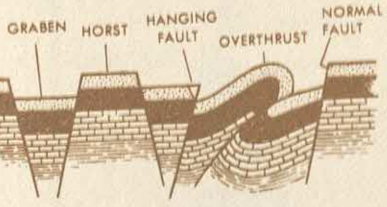
BIOLOGY. An individual living plant or animal; also, any living thing.

Two characteristics of any ORGANISM *are the abilities to reproduce and to carry on respiration.*

origin \ˈȯr-ə-jən\ *n.*

1. BIOLOGY. The ancestry, or line of descent, of an organism or group of organisms. 2. ANATOMY. The larger or more central end of a muscle that attaches to a bone it does not move. 3. MATHEMATICS. The point labeled 0 on a number line or scale; also, the intersection of the axes of a coordinate system.

The probable ORIGIN *of mammals and birds was reptiles.*



OROGENY
(COMMON RESULTS)

ornithology \ˌȯr-nə-ˈthäl-ə-jē\ *n.*

ZOOLOGY. The science of the groups, forms, habits and development of birds.

ORNITHOLOGY *is a favorite hobby of many scientists.*

orogeny \ȯ-ˈräj-ə-nē\ *n.*

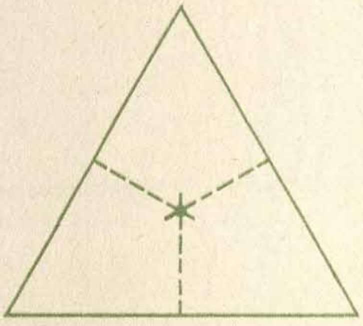
EARTH SCIENCE. The formation of mountains through such processes as folding and faulting.

The Appalachian Revolution was a period of OROGENY *during which the Appalachian Mountains were formed.*

orthocenter \'ȯr-thə-ˌsen-tər\ *n.*

MATHEMATICS. The point within a triangle where the three altitudes of the triangle intersect.

The ORTHOCENTER *of an equilateral triangle is equidistant from all three sides.*



ORTHOCENTER
OF EQUILATERAL TRIANGLE

orthogenesis \ˌȯr-thə-'jen-ə-səs\ *n.*

BIOLOGY. A theory that evolution is caused and controlled by unknown perfecting laws, or laws of growth, and that species change along predetermined lines regardless of environmental conditions.

According to ORTHOGENESIS, *the Irish elk was destined to develop the gigantic antlers believed to have contributed to its extinction.*

orthogonal \ȯr-'thäg-ən-ᵊl\ *adj.*

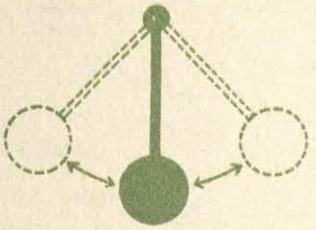
MATHEMATICS. Right-angled, or pertaining to right angles.

If the tangents drawn to two intersecting circles at a point of intersection are perpendicular, the circles are said to be ORTHOGONAL *circles.*

oscillate \'äs-ə-ˌlāt\ *v.*

PHYSICS. To move in a regular manner from side to side or back and forth.

The electrons in regular house current OSCILLATE *sixty times per second.*



OSCILLATE

oscillator \'äs-ə-ˌlāt-ər\ *n.*

PHYSICS. An electronic device that produces high-frequency alternating current. When used in broadcasting radio waves, its principal use, the frequencies may range from 10 kilocycles to 30 million kilocycles per second.

An OSCILLATOR *may be based on the action of certain electron tubes or specific types of crystals.*

oscillograph \ä-'sil-ə-ˌgraf\ *n.*

PHYSICS. A device that records variations of electrical quantity as a continuous curve drawn on graph paper or produced photographically on sensitized film.

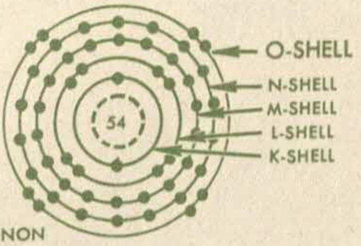
An OSCILLOGRAPH *can be used to make a visual record of the fluctuating voltage of a varying electrical current.*

OSCILLOSCOPE

oscilloscope \ä-'sil-ə-ˌskōp\ *n.*

PHYSICS. An electronic instrument that shows on a fluorescent screen the changes in a varying electric voltage during a short time interval. By means of auxiliary devices, other forms of energy, such as sound or radio waves, may be changed into a varying electrical voltage and may also be shown on the screen.

In medical research, the OSCILLOSCOPE *has been used to make a detailed study of heart action.*



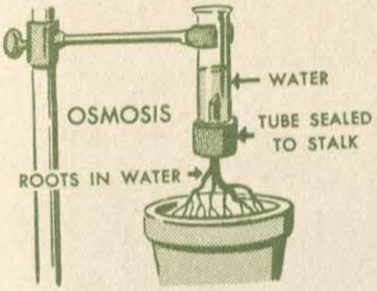
XENON
(ATOM)

O-shell \'ō-ˌshel\ *n.*
CHEMISTRY and PHYSICS. One of the seven principal energy levels, identified by the letters K, L, M, N, O, P and Q, that electrons may occupy in an atom; the fifth principal energy level that electrons may occupy in the Bohr model for the atom.

An atom of silver has only one electron in its O-SHELL.

osmosis \ä-'smō-səs\ *n.*
1. BIOLOGY. The diffusion of liquid through a living, semipermeable membrane from a side containing less dissolved or suspended particles to the side containing a greater concentration of particles. 2. CHEMISTRY. The process by which a solvent diffuses from one solution into another solution of higher concentration through a semipermeable membrane. Osmosis tends to equalize the concentrations on both sides of the membrane.

In the body, tissue fluid moves from the tissue into blood vessels by OSMOSIS.



osmotic pressure \ä-'smät-ik 'presh-ər\
CHEMISTRY and PHYSICS. The difference in pressure between two solutions, or suspensions, of different concentration on opposite sides of a membrane that is permeable to the solvent only. Osmotic pressure is caused by a net diffusion of solvent toward the more concentrated solution or suspension. It is measured as the pressure that, when applied to the more concentrated solution or suspension, will prevent the movement of additional solvent into the solution or suspension.

Red blood cells placed in pure water will swell and burst as a result of OSMOTIC PRESSURE.

ossify \'äs-ə-ˌfī\ *v.*
PHYSIOLOGY and ZOOLOGY. To become, or be changed into, bone.

Cartilage in the wrists of young children will later OSSIFY *into wristbones.*

osteology \\ˌäs-tē-ˈäl-ə-jē\\ *n.*

1. MEDICINE. The study of the bones of man and other vertebrate animals. 2. ANATOMY and ZOOLOGY. The set of bones making up a skeleton or a part of it.

OSTEOLOGY *has made it possible for doctors to correct many defects in human bone structure.*

OUTCROP

ostiole \\ˈäs-tē-ˌōl\\ *n.*

ANATOMY. A small opening or pore.

Each pore through which perspiration reaches the skin is an OSTIOLE.

ounce \\ˈau̇n(t)s\\ *n.*

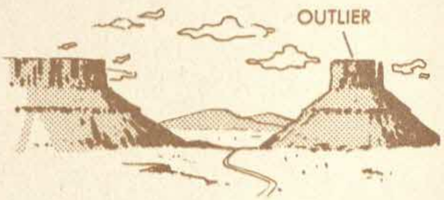
MATHEMATICS. A unit of weight that is equal to $\frac{1}{16}$ pound in avoirdupois weight, or $\frac{1}{12}$ pound in troy or apothecaries' weight.

An OUNCE *is equivalent to 28.3495 grams.*

outcrop \\ˈau̇t-ˌkräp\\ *n.*

EARTH SCIENCE. An exposure of bedrock; also, a vein or any rock strata at the earth's surface.

An OUTCROP *may occur when materials overlying bedrock are carried away by running water.*



OUTLIER

outlier \\ˈau̇t-ˌlī(-ə)r\\ *n.*

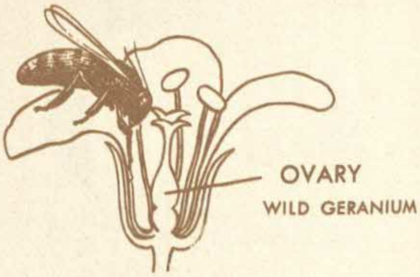
EARTH SCIENCE. An isolated group of rocks or a detached formation that was once part of a larger formation but that became separated by erosion. An outlier is surrounded by underlying rocks of older age.

A butte is an OUTLIER.

output \\ˈau̇t-ˌpu̇t\\ *n.*

PHYSICS. The energy or signal produced by a device or machine; especially, the electrical energy or electrical signal produced by devices such as transformers or oscillators; also, a quantity of energy or an intensity of signal.

The efficiency of any machine is the ratio of the OUTPUT *to the input.*



ovary \\ˈōv-(ə-)rē\\ *n.*

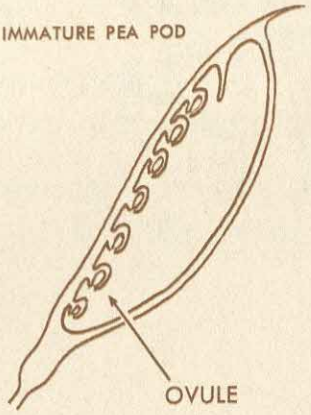
BIOLOGY. A female organ of reproduction. It produces eggs in animals and megaspores in plants.

A fruit is a ripened OVARY.

overburden \'ō-vər-ˌbərd-ᵊn\ *n.*

EARTH SCIENCE. The earth material covering a mineral deposit, especially one that can be mined in an open pit; also, loose sand and gravel lying above bedrock.

Coal may be mined in open pits, or strip mines, if the OVERBURDEN *is not too thick.*



overtone \'ō-vər-ˌtōn\ *n.*

PHYSICS. A certain frequency that is a multiple of the fundamental frequency of a vibrating or oscillating system. It is usually applied to sound energy.

An OVERTONE *contributes to the quality of a musical tone.*

oviparous \ō-'vip-(ə-)rəs\ *adj.*

ZOOLOGY. Descriptive of the reproductive pattern in which eggs are expelled from the body of the female and offspring subsequently hatch from the eggs.

All birds are OVIPAROUS, *but some fish and reptiles are not.*

ovule \'ō-(ˌ)vyü(ə)l\ *n.*

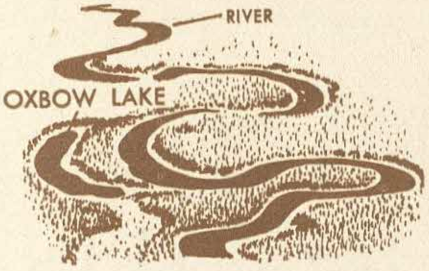
BOTANY. In seed plants, the sac or body in which the egg forms and which contains the female gametophyte. After fertilization of the egg, the ovule develops into a seed.

An OVULE *is technically known as a megasporangium.*

ovum \'ō-vəm\ *n.*

BIOLOGY. An egg cell; see *egg.*

A fertilized OVUM *is the very first stage in the life of an organism.*



oxbow lake \'äks-ˌbō 'lāk\

EARTH SCIENCE. A crescent-shaped lake formed by a cutoff that isolates a bend, or meander, from the main stream.

An OXBOW LAKE *is usually found in very wide and quite level valleys.*

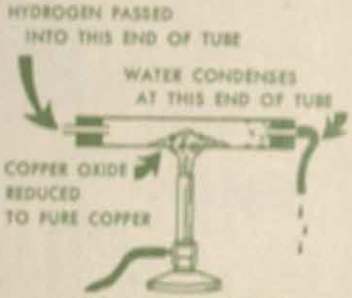
oxidation \ˌäk-sə-'dā-shən\ *n.*

CHEMISTRY. The chemical reaction of a substance with oxygen that results in one or more oxides; also, a reaction that causes an atom or an ion to lose one or more electrons.

The slow OXIDATION *of aluminum in air produces an airtight film of aluminum oxide that prevents further oxidation.*

oxidation-reduction reactions \ˌäk-sə-ˈdā-shən ri-ˈdək-shən rē-ˈak-shənz\
CHEMISTRY. Reactions that involve a transfer of one or more electrons from one atom or ion (oxidation) to another atom or ion (reduction).

Most common inorganic reactions are OXIDATION-REDUCTION REACTIONS *that give off heat as they occur.*



$CuO + H_2 \rightarrow Cu + H_2O$

OXIDATION-REDUCTION
REACTION

oxide \ˈäk-ˌsīd\ *n.*
CHEMISTRY. A compound of oxygen and one other element, or radical.

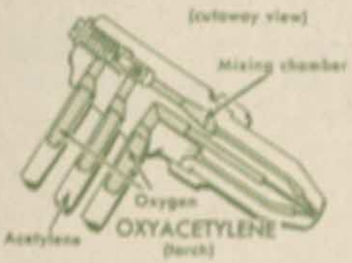
Hematite is an OXIDE *of iron.*

oxidizer \ˈäk-sə-ˌdī-zər\ *n.*
1. CHEMISTRY. A substance that accepts electrons in a chemical reaction. 2. ASTRONAUTICS. A component of rocket propellants that supports the burning of the fuel.

Liquid oxygen, like nitric acid and hydrogen peroxide, is commonly used as an OXIDIZER *in rockets.*

oxidizing agent \ˈäk-sə-ˌdīz-iŋ ˈā-jənt\
CHEMISTRY. A compound of oxygen that decomposes relatively easily and, by so doing, provides oxygen that can react with something else; also, an atom, ion or molecule that, in chemical reactions, tends to take electrons from other atoms, ions or molecules, causing them to become oxidized.

Potassium nitrate is an OXIDIZING AGENT *used in making black gunpowder.*



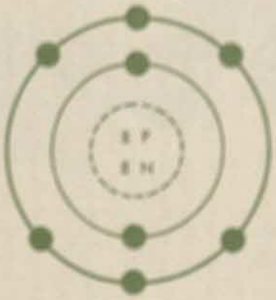
OXYACETYLENE
(torch)

oxyacetylene \ˌäk-sē-ə-ˈset-ᵊl-ən\ *adj.*
CHEMISTRY. Pertaining to the process of burning acetylene in oxygen to produce a very hot flame.

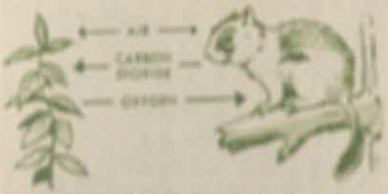
Welders frequently use an OXYACETYLENE *torch to create intense heat.*

oxygen \ˈäk-si-jən\ *n.*
CHEMISTRY. A colorless, odorless gas at ordinary temperatures, the most abundant element by weight in the known portions of the earth. Oxygen combines chemically with most other elements to form oxides. Symbol, O; atomic number, 8; atomic weight, 15.9994.

Most of the earth's OXYGEN *combines either with hydrogen to form water or with silicon to form silicon dioxide or silicate compounds.*



OXYGEN
(ATOM)



OXYGEN-CARBON-DIOXIDE CYCLE

oxygen-carbon-dioxide cycle \'äk-si-jən 'kär-bən (')dī-'äk-sīd 'sī-kəl\
BIOLOGY. The exchange of gases between plants and animals. Plants and animals take in oxygen and give off carbon dioxide during respiration, but plants utilize carbon dioxide and give off oxygen during photosynthesis.

The OXYGEN-CARBON-DIOXIDE CYCLE *is part of the interdependence of living things.*

oxyhemoglobin \,äk-si-'hē-mə-,glō-bən\ *n.*
PHYSIOLOGY and ZOOLOGY. A substance in the blood of many animals that is composed of hemoglobin combined with two atoms of oxygen.

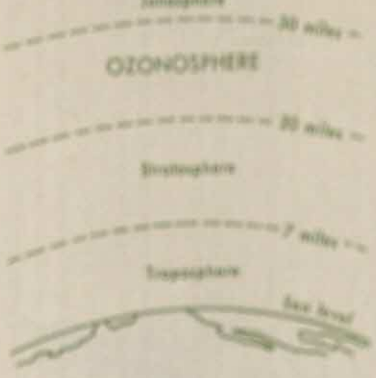
OXYHEMOGLOBIN *has a bright red color.*

oxyhydrogen \,äk-si-'hī-drə-jən\ *adj.*
CHEMISTRY. Pertaining to the process of burning hydrogen in oxygen to produce a hot flame.

The only chemical product of the flame from an OXYHYDROGEN *torch is water vapor.*

ozokerite \,ō-zō-'ki(ə)r-,īt\ *n.*
EARTH SCIENCE. A mineral composed of a mixture of hydrocarbons. It is a waxlike substance, colorless to white when pure, but greenish, yellowish or brown when impure. It is used in making candles and in electrotyping.

Some varieties of OZOKERITE *have an unpleasant odor.*



ozone \'ō-,zōn\ *n.*
CHEMISTRY and EARTH SCIENCE. A molecular form of oxygen having three atoms of oxygen per molecule (O_3) instead of two (O_2), as is characteristic of the usual oxygen. Ozone has a distinct odor, is chemically more reactive than ordinary oxygen and is formed at high altitudes by ultraviolet light from the sun interacting with molecular oxygen.

OZONE *can be produced in the laboratory by passing an electrical discharge through air or a container of oxygen.*

ozonosphere \ō-'zō-nə-,sfi(ə)r\ *n.*
EARTH SCIENCE. A layer of the atmosphere which occurs at about twenty to thirty miles above the earth's surface. Its main characteristics are its large ozone content and relatively high temperature. The high temperature results from great absorption of the sun's ultraviolet radiation.

The OZONOSPHERE *is a rather narrow layer of the atmosphere.*

P

pahoehoe \pə-'hō-ē-,hō-ē\ *n.*

EARTH SCIENCE. Basaltic lava that flows and hardens with a billowy, ropy or wrinkled surface.

PAHOEHOE is one of the types of lava occurring on the island of Hawaii.

paleontology \,pā-lē-(,)än-'täl-ə-jē\ *n.*

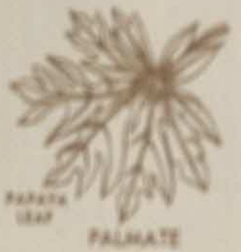
EARTH SCIENCE. The scientific study of life in past geologic time, based on plant and animal fossils; the study of fossils.

The fossil evidence studied in PALEONTOLOGY indicates the evolutionary nature of life.

palisade layer \,pal-ə-'sād 'lā-ər\

BOTANY. A tissue of compactly- and regularly-arranged cells that lies between the upper and lower epidermis in leaves. Sugar is manufactured within it, and, with the spongy layer, it makes up the mesophyll.

Through a microscope, the PALISADE LAYER appears as a layer of cells having their long axes perpendicular to the surface of the leaf.



palmate \'pal-,māt\ *adj.*

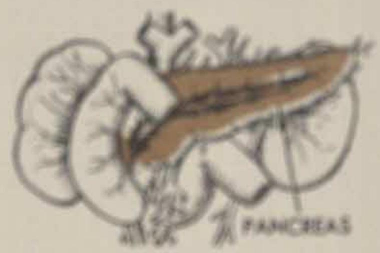
BOTANY. Referring to structures that radiate from a center, as the veins of a leaf or the leaflets of a compound leaf.

The leaves of the tropical papaya tree and of the temperate buckeye tree have PALMATE forms.

panchromatic \,pan-krō-'mat-ik\ *adj.*

PHYSICS. Referring to photographic film that is sensitive to all frequencies of visible radiation, although it is usually not equally sensitive to all frequencies.

PANCHROMATIC film is generally used in simple cameras for black-and-white pictures.



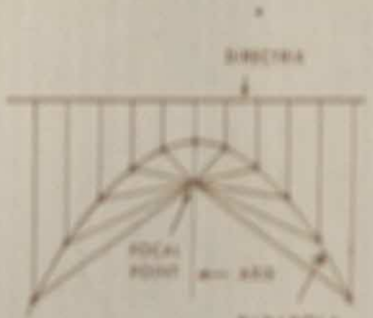
pancreas \'paŋ-krē-əs\ *n.*

ANATOMY. A large digestive gland located behind the stomach and somewhat parallel to the duodenum into which it secretes the pancreatic juice. It also contains the islands of Langerhans that produce insulin.

Such digestive enzymes as amylase, lipase and trypsin are produced in the PANCREAS.

panleucopenia \ˌpan-ˌlü-kə-ˈpē-nē-ə\ n.
MEDICINE and BIOLOGY. A serious virus disease of cats, characterized by diarrhea, fever and extensive destruction of white blood cells; also called feline distemper.

Although PANLEUCOPENIA *is usually fatal, cats can be immunized against it.*



PARABOLA

parabola \pə-ˈrab-ə-lə\ n.
MATHEMATICS. A set of points, each of which is equidistant from a given point called the focus and from a given line called the directrix. A parabola is the conic section formed when a plane parallel to the side of the cone intersects the cone.

A PARABOLA *is a plane curve.*

parabolic \ˌpar-ə-ˈbäl-ik\ adj.
MATHEMATICS. Referring to, or generated by, a parabola.

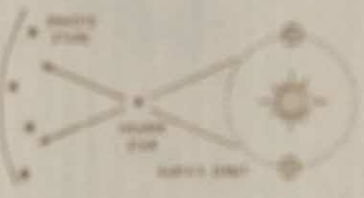
A PARABOLIC *cylinder is a cylindrical surface whose directrix is a parabola.*

paralimnic \ˌpar-ə-ˈlim-nik\ adj.
BIOLOGY and EARTH SCIENCE. Pertaining to the shoreline or shallow of a freshwater body.

Many kinds of free-living organisms inhabit the PARALIMNIC *zone.*

parallax \ˈpar-ə-ˌlaks\ n.
1. ASTRONOMY. The apparent change in position of a relatively-nearby celestial body with respect to background stars, when it is viewed from two locations. The apparent change is due to a change in position of the observer rather than to the motion of the celestial body. 2. PHYSICS. The apparent change in position of an object, such as an indicating needle on an electric meter, as a result of observations from different positions or angles.

PARALLAX *can be demonstrated by looking at a nearby object against a fixed background alternately with the right and then the left eye.*



PARALLAX

parallel \ˈpar-ə-ˌlel\ adj.
1. MATHEMATICS. In Euclidean geometry, referring to straight lines in a plane that do not meet, however far extended, and to planes or to straight lines and planes that do not meet, regardless of how far they are produced. 2. PHYSICS. Referring to an electric current in which the entering stream of electrons is separated into two or more branches that rejoin to complete the circuit.

Two intersecting pairs of PARALLEL *lines form a parallelogram.*

parallelogram \ˌpar-ə-ˈlel-ə-ˌgram\ *n.*
MATHEMATICS. A four-sided polygon, or quadrilateral, whose opposite sides are parallel.

A diagonal of a PARALLELOGRAM *divides it into two congruent triangles.*

paramagnetic \ˌpar-ə-(ˌ)mag-ˈnet-ik\ *adj.*
PHYSICS. Attracted to a magnet, but not so strongly as iron is attracted; also, referring to something through which a magnetic field will pass more easily than through air, or to something having greater magnetic permeability than air.

Liquid oxygen and the rare-earth elements are PARAMAGNETIC.

parameter \pə-ˈram-ət-ər\ *n.*
1. MATHEMATICS. A letter used in an expression or an equation that plays an auxiliary role and to which a number, or constant, may be assigned to represent a specific case; also, in statistics, an assumed set of values in a probability distribution. 2. One of a set of variables that describe or define a condition or an event, such as the one that specifies time or the three variables necessary to define the position of an object.

The equation $y = mx + 3$ *represents a set, or family, of lines, each of whose y-intercept is 3 and whose slope depends upon the number that replaces the* PARAMETER *m.*

parasite \ˈpar-ə-ˌsīt\ *n.*
BIOLOGY. An organism that lives intimately in, or on, a host organism from which it derives nourishment. It is generally detrimental to the host.

The tapeworm is a well-known PARASITE.

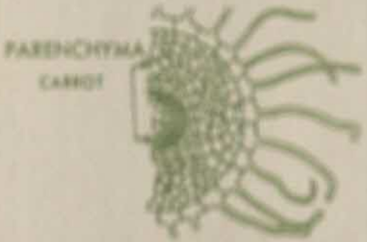
PARATHYROID GLANDS

parasympathetic \ˌpar-ə-ˌsim-pə-ˈthet-ik\ *adj.*
PHYSIOLOGY. Referring to the part of the nervous system that controls certain involuntary reactions. It performs in opposition to the sympathetic nervous system and thus acts as a check-and-balance system.

The vagus nerve, one of the PARASYMPATHETIC *nerves, slows down heart action.*

parathyroid glands \ˌpar-ə-ˈthī(ə)r-ˌȯid ˈglandz\
ANATOMY. Four small endocrine glands imbedded in the back part of the thyroid gland, two on each side, that produce hormones controlling the use of calcium and phosphorus in the body.

When the PARATHYROID GLANDS *cease functioning, spasms, twitching of muscles and convulsions occur.*

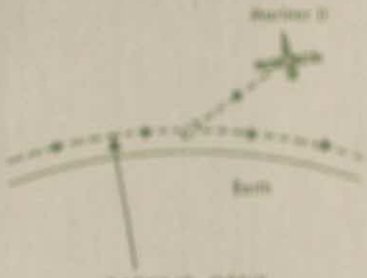


parenchyma \pə-'reŋ-kə-mə\ *n.*
1. BOTANY. Thin-walled plant tissue, such as that in the soft parts of roots, stems and leaves and in many edible fruits.
2. ANATOMY. The cells of an organ or tissue that carry on the functions of the organ or tissue, as contrasted with connective tissue cells that make up the framework of the organ or tissue.
3. ZOOLOGY. The endoplasm of one-celled animals.

PARENCHYMA is the most prominent internal tissue at the growing tip of a stem.

parking orbit \'pärk-iŋ 'ȯr-bət\
ASTRONAUTICS. A stable orbit at a predetermined height above the earth's surface. The first stage of a two-stage rocket might place the vehicle in this orbit, and the firing of the second rocket might send it farther out into space.

The Mariner II Venus probe was launched from a PARKING ORBIT 115 miles above the earth.



PARKING ORBIT
(OF MARINER II)

parsec \'pär-ˌsek\ *n.*
ASTRONOMY. The distance at which a star would have a *parallax* of one second when viewed from two positions one astronomical unit apart. The parsec is equal to 3.26 light-years, 206,265 astronomical units or about 19.2 trillion miles.

The PARSEC and the light-year are convenient units for measuring the distances to stars.

parthenogenesis \ˌpär-thə-nō-'jen-ə-səs\ *n.*
BIOLOGY. The development of an embryo without fertilization of the egg. It occurs naturally among some invertebrate animals, and has been artificially induced in some vertebrates.

While bees produced by PARTHENOGENESIS develop as males, parthenogenetic mammals develop into females.

partial fractions \'pär-shəl 'frak-shənz\
MATHEMATICS. In algebra, a set of fractions that have a sum equal to a given fraction and whose denominators are the factors of the denominator of the given fraction.

Simple algebraic methods may be used to find the PARTIAL FRACTIONS of most proper, rational fractions.

PARTHENOGENESIS

partial pressure \'pär-shəl 'presh-ər\
CHEMISTRY and PHYSICS. Referring to the pressure exerted by one gas when it is mixed with another gas.

Dalton's law of PARTIAL PRESSURES states that the pressure of a mixture of gases is equal to the sum of the pressures the gases would exert if confined separately within the same volume.